International Journal of Scientific Research and Engineering Development-– Volume 9 Issue 5, Sep-Oct 2026
Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

Global Innovations in Bioremediation and Resource Recovery for Sustainable Legacy Waste Management at Vellalore Dumpsite, India

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Abstract:

Accelerated urbanization has left a trail of unmanaged municipal solid waste (MSW) dumpsites globally, locking up valuable urban land and presenting continuous ecological threats. Dumpsite reclamation via biomining and bioremediation has emerged as a globally validated methodology to close open landfills sustainably. This review paper synthesizes state-of-the-art biological strategies utilized across developed nations (such as Germany, Japan, and South Korea) for legacy landfill rehabilitation and draws a critical comparative analysis with the ongoing Phase-II biomining project at the Vellalore Dump Yard in Coimbatore, Tamil Nadu. The Vellalore site faces severe regulatory scrutiny over processing throughput limitations, toxic odor emissions (H2S and NH3), and hazardous leachate permeation into local aquifers. By benchmarking against international biotechnological practices, this paper provides a specialized translation roadmap. We detail the metabolic pathways of tailored microbial consortia, kinetic monitoring tools, and specific heavy metal immobilization mechanisms required to transform Vellalore from a chronic civic liability into a safe, circular economy model.

Keywords — **Municipal Solid Waste (MSW), Biomining, Bioremediation, Landfill Rehabilitation, Circular Economy**

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1. INTRODUCTION

The rapid expansion of urban populations, industrialization, and consumer-driven economies has resulted in an unprecedented increase in municipal solid waste (MSW) generation worldwide (Kaza et al., 2018). Recent global estimates indicate urban centers generate more than 2 billion tonnes of MSW annually, a figure projected to rise substantially due to population growth, shifting lifestyles, and accelerated economic development (Ferronato & Torretta, 2019). In numerous developing countries,
MSW continues to be disposed of in open dumpsites and poorly engineered landfills, creating long-term ecological, economic, and public health challenges (Kumar et al., 2017).

Legacy waste dumpsites represent one of the most persistent environmental burdens associated with historical waste disposal practices. Unlike engineered sanitary landfills, legacy dumpsites were developed without adequate environmental safeguards such as leachate collection systems, gas recovery infrastructure, impermeable liners, and systematic waste segregation mechanisms (Hogland et al., 2004). Consequently, these sites continue to generate harmful emissions, contaminate groundwater resources, occupy valuable urban land, and pose significant risks to surrounding communities long after waste deposition has ceased (Quaghebeur et al., 2013).

The environmental impacts associated with unmanaged legacy dumpsites include greenhouse gas emissions, toxic leachate generation, odor pollution, spontaneous combustion, biodiversity loss, and the accumulation of hazardous contaminants such as heavy metals and persistent organic pollutants (Christensen et al., 2001). Among these impacts, methane (CH4) emissions are highly significant due to their contribution to global climate change. During the anaerobic decomposition of organic matter in deep waste layers, methane is generated alongside carbon dioxide (CO2) by specialized microbial consortia (Jain et al., 2014). Methane possesses a global warming potential approximately 28 times greater than carbon dioxide over a 100-year period, making unmanaged dumpsites critical contributors to anthropogenic greenhouse gas emissions (Bogner et al., 2011). Simultaneously, the anaerobic degradation of sulfur-containing organic compounds and nitrogenous matter generates volatile sulfur compounds (VSCs), hydrogen sulfide (H_2S), ammonia (NH_3), and volatile organic compounds (VOCs) that induce respiratory disorders, headaches, skin irritation, and reduced quality of life in adjacent residential regions (Scheutz et al., 2009).

Leachate generation represents another critical barrier to environmental safety. Rainwater infiltrating waste layers dissolves organic and inorganic contaminants, producing a highly polluted liquid containing dissolved organic carbon, ammoniacal nitrogen, heavy metals, xenobiotic compounds, and pathogenic microorganisms (Renou et al., 2008). In the absence of appropriate containment systems, leachate migrates through soil profiles and contaminates groundwater aquifers, threatening drinking water resources and agricultural productivity (Joseph et al., 2003).

The Vellalore Waste Management Facility in Coimbatore, Tamil Nadu, encompasses over 650 acres of land and contains millions of tonnes of mixed legacy MSW (CCMC, 2025). For several decades, the site functioned as the primary disposal location for municipal solid waste generated within the rapidly expanding Coimbatore metropolitan region. The absence of comprehensive segregation, treatment, and environmental control measures contributed to severe environmental problems, including groundwater contamination, odor emissions, vector proliferation, and periodic landfill fires (TNPCB, 2025).

The Coimbatore City Municipal Corporation (CCMC) is currently executing its Phase-II biomining operation to clear a target mass of 7.94 lakh metric tonnes across 84.62 acres (CCMC, 2025). While open dumping has officially stopped and over 53% of this target waste has been processed using basic mechanical sifting, the project is under intense pressure from the National Green Tribunal (NGT) and the Tamil Nadu Pollution Control Board (TNPCB) due to significant operational shortfalls (Joseph & Rajesh, 2024):

Throughput Inadequacy: Current mechanical lines processing 900–1,100 Tonnes Per Day (TPD) are moving too slowly to meet upcoming statutory closure deadlines.

Atmospheric Pollution: Unmanaged organic fractions undergo anaerobic putrefaction, releasing highly offensive odors, primarily Hydrogen Sulfide (H_2S) and Ammonia (NH_3), causing severe respiratory distress in neighboring communities like Podanur and Chettipalayam.

Aquifer Degradation: Rainwater percolating through raw legacy mounds generates highly toxic, black leachate that escapes into local aquifers, turning borewell water yellow and increasing Total Dissolved Solids (TDS) well past permissible drinking limits.

Mechanical sorting alone cannot resolve these challenges because it treats the physical symptoms of the waste mound without stabilizing its biochemical activity (CPCB, 2019). The transition from conventional mechanical biomining toward integrated bioprocess engineering offers significant opportunities for improving operational outcomes at Vellalore. By incorporating microbial pretreatment systems, enzyme-assisted degradation pathways, methane mitigation technologies, and heavy metal bioremediation mechanisms, it is possible to accelerate waste stabilization while enhancing environmental performance (Hermann et al., 2021).

2. GLOBAL COMPARATIVE FRAMEWORK:

To optimize the Vellalore remediation pipeline, standard European and Asian biotechnological landfill reclamation protocols must be contrasted with the baseline conditions observed at Vellalore.

3. BIOTECHNOLOGICAL SOLUTION FOR DUMPSITE STABILIZATION

Integrating biotechnology into the biomining framework transforms legacy waste from a volatile mass into a stable, easily separable matrix through precise chemical and microbial pathways.

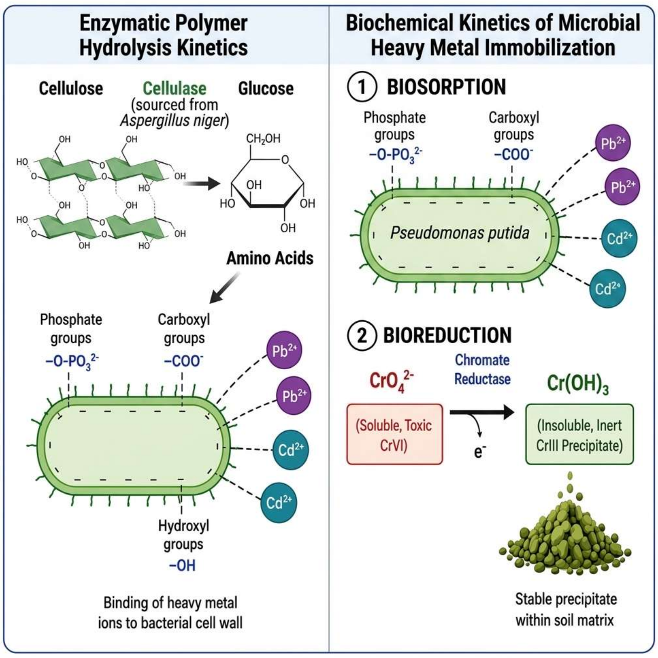

Fig. 1 : Biotechnological solution for dumpsite stabilization

3.1. Mechanistic Homofermentative Acidification for Odor Elimination

In central European landfill reclamation models, raw excavation is prohibited due to the immediate risk of pathogenic dispersion and odor clouds (Hermann et al., 2021).

- **The Metabolic Pathway:** Spraying Lactobacillus plantarum at a minimum density of 1 ×10^9 CFU/mL shifts the organic waste degradation pathway from anaerobic putrefaction to clean lactic acid fermentation via the Embden-Meyerhof-Parnas pathway (Kandler, 1983).
- **Biochemical Kinetics:** Biochemical Kinetics: The bacteria consume soluble mono- and disaccharides present in organic food waste, converting them into lactic acid (CH3CHOHCOOH) (Leroy & De Vuyst, 2004). This drops the localized pH from a neutral 7.0 down to an acidic 4.0–4.5 within 48 to 72hours (Axelsson, 2004).
- **Application for Vellalore:** This rapid acidification causes an immediate acid shock to anaerobic, putrefying pathogens (Clostridium, Salmonella). It deactivates the microbial enzymes responsible for breaking down sulfur-containing proteins, completely shutting down the production of foul-smelling gases like H_2S and NH_3 (Wang & Zhang, 2023). Furthermore, it destroys the soft cellular membranes of fly and mosquito larvae (maggots), breaking the vector breeding cycle directly at the mound surface without chemical pesticides.

3.2. Enzymatic Polymer Hydrolysis Kinetics for Accelerated Sifting

In highly populated East Asian tech centers, land area constraints require accelerated biomining through concentrated enzyme cocktails to break down organic binding structures rapidly (Kim et al., 2022).

- **The Metabolic Pathway:** Following the acidification stage, the windrows are mechanically aerated using earthmovers. As oxygen is introduced, the pH naturally self-neutralizes back to a range of 6.5–7.2, triggering the rapid growth of spore-forming aerobic bacteria and fungi: *Bacillus subtilis*, *Bacillus licheniformis*, and *Aspergillus niger* (Baldrian, 2008).
- **Biochemical Kinetics:** These microbes secrete powerful extracellular enzymes directly into the matrix to drive macromolecular cleavage (Sánchez, 2009). Cellulases break down long-chain cellulose into simple glucose monomers, while proteases sever peptide bonds in proteins to release water molecules trapped within the organic structure (Lynd et al., 2002; Singh et al., 2019)

- **Application for Vellalore:** Currently, wet and sticky degraded organic matter binds tightly to old plastics, causing heavy clogging and jamming inside the mechanical trommel screens at Vellalore, forcing frequent operational shutdowns (CCMC, 2025). Deploying this targeted enzyme roster rapidly dissolves the sticky organic "glue", breaks the cell walls of organic matter, and releases trapped moisture. Combined with solar windrow turning, it dries the waste matrix from > 50% down to a fluid < 25% moisture content. This eliminates screen clogging, ensures crisp separation of the Refuse-Derived Fuel (RDF) fraction, and doubles the daily processing capacity of the existing trommels.

3.3. Microbial Bioremediation and Immobilization of Heavy Metals

A major challenge with the fine earth fraction (< 4 mm) recovered from Indian dumpsites is the high concentration of toxic heavy metals like Lead (Pb), Cadmium (Cd), and Chromium (Cr), which leach from dumped electronic and industrial waste (CPCB, 2019).

- **The Metabolic Pathway:** Incorporating metal-tolerant, bio-sorbent bacterial strains like *Pseudomonas putida* and *Cupriavidus metallidurans* into the secondary windrow stage targets these toxic ions (Nies, 1999).

- **Application for Vellalore:** Currently, the fine soil fraction recovered from Vellalore cannot be easily sold or used because of heavy metal toxicity fears (Joseph & Rajesh, 2024). Integrating these bioremediation pathways permanently locks the heavy metals into an insoluble, non-bioavailable form within the soil matrix (Gadd, 2020). This ensures that the final Enriched Bio-Earth passes ecotoxicological screening and can be safely distributed for local agricultural or highway greening projects.

4. COMPREHENSIVE RESEARCH GAP ANALYSIS

Despite substantial global progress in landfill reclamation technologies, significant knowledge gaps remain regarding the integration of microbial engineering, enzyme-assisted stabilization, and heavy metal bioremediation within large-scale biomining operations in tropical environments (Kumar et al., 2017). Most existing studies focus on isolated treatment components rather than comprehensive systems-level frameworks capable of addressing multiple environmental challenges simultaneously (Frändegård et al., 2013).

4.1. Identified Core Research Gaps

- **Gap 1: Predominant Focus on Mechanical Biomining Rather Than Biological Stabilization:** Most biomining projects currently implemented in developing countries primarily emphasize mechanical excavation, trommel screening, density separation, and material recovery operations (CPCB, 2019). These approaches fail to address the fundamental biological instability of excavated waste. Organic fractions continue to undergo uncontrolled anaerobic decomposition, generating methane, carbon dioxide, hydrogen sulfide, ammonia, and VOCs. There is a lack of integrated studies evaluating how targeted microbial consortia can be used as a mandatory pre-treatment stage to reduce odors, suppress pathogens, and improve material separation efficiency.

- **Gap 2: Limited Application of Microbial Consortia Engineering:** Most landfill remediation studies treat microbial activity as a naturally occurring process rather than an engineering parameter that can be optimized (Tyagi et al., 2011). Current literature largely overlooks engineered microbial consortia, synthetic microbial communities, sequential microbial treatment systems, and functional microbial succession—particularly the integration of *Lactobacillus* spp., *Bacillus* spp., *Aspergillus* spp., *Pseudomonas* spp., and methanotrophic bacteria within a single biomining framework (Thompson et al., 2005).

- **Gap 3: Lack of Enzyme-Based Acceleration Strategies:** Biological degradation of legacy waste is often constrained by the slow breakdown of lignocellulosic materials, proteins, fats, and complex organic polymers (Sánchez, 2009). Current biomining projects generally depend on natural composting, periodic turning, and passive aeration, which require extended processing periods. There is a significant absence of research quantifying the effects of exogenous enzyme supplementation on waste stabilization kinetics and overall throughput under tropical climatic conditions (Kim et al., 2022).
- **Gap 4: Inadequate Heavy Metal Remediation in Recovered Soil Fractions:** Existing studies largely focus on metal concentration measurements, risk assessments, and disposal recommendations, while comparatively little attention has been given to biological detoxification approaches integrated directly into the stabilization process (Fu & Wang, 2011).
- **Gap 5: Absence of Systems Biology Approaches:** Current landfill remediation studies typically evaluate individual parameters in isolation. The application of systems biology, metabolic network analysis, and ecological modeling remains extremely limited (Caspi et al., 2022).
- **Gap 6: Lack of Metagenomic and Functional Microbial Characterization:** Traditional landfill studies rely heavily on culture-based microbiology techniques, which fail to capture over 95% of environmental microorganisms that cannot be cultured (Simon & Daniel, 2011). Modern technologies such as shotgun metagenomics, metatranscriptomics, metabolomics, and functional gene profiling are rarely incorporated into biomining investigations (Quince et al., 2017).
- **Gap 7: Insufficient Climate Change Assessment:** Few biomining projects quantify carbon footprint reduction, methane mitigation potential, and life-cycle environmental benefits of biologically enhanced biomining systems via comprehensive life cycle assessment (LCA) and carbon accounting studies (Finnveden et al., 2009).
- **Gap 8: Lack of Tropical Context-Specific Models:** A substantial portion of landfill remediation literature originates from temperate regions. Tropical regions exhibit higher temperatures, seasonal monsoon patterns, greater organic waste content, different microbial ecology, and distinct socioeconomic constraints, meaning direct transfer of technologies may not yield comparable results.
- **Gap 9: Absence of Integrated Decision-Support Frameworks:** Emerging technologies such as Artificial Intelligence (AI), Machine Learning (ML), Digital Twins, and Predictive Environmental

Modeling have received limited attention in biomining research.

Identified Core Research Gap: Based on the literature review, the most significant scientific gap is the absence of an integrated, microbiologically engineered biomining framework that combines microbial consortium engineering, enzyme-assisted waste stabilization, methane and odor mitigation, heavy metal bioremediation, metagenomic monitoring, life-cycle environmental assessment, and AI-assisted process optimization within a single operational model for tropical legacy dumpsites.

5. ECOTOXICOLOGICAL MONITORING PROTOCOL FOR VELLALORE VALIDATION

To successfully transition this research into a verifiable field project at Vellalore, a strict, laboratory-backed analytical protocol must be maintained to validate environmental safety.

5.1. Gaseous Emissions Tracking

Ambient air at the windrow boundaries must be sampled weekly using Gas Chromatography-Mass Spectrometry (GC-MS) to confirm the complete drop in volatile sulfur compounds and air pollution markers. This verifies the functional efficiency of the initial *Lactobacillus* pre-treatment (Scheutz et al., 2009).

5.2. Abiotic Heavy Metal Profiling

Samples of the processed sub-4mm Bio-Earth must be digested in concentrated nitric acid (HNO3) and analyzed via Atomic Absorption Spectroscopy (AAS) or Inductively Coupled Plasma Mass Spectrometry (ICP-MS). This step ensures that free heavy metal concentrations fall safely below the limits mandated by the Central Pollution Control Board (CPCB) Solid Waste Management Rules (CPCB, 2019).

5.3. Biotic Phytotoxicity Bioassays

The **Seed Germination Index (GI%)** is one of the most widely used biological indicators for evaluating compost maturity and phytotoxicity. Unlike physicochemical analyses, the GI assay directly measures the effects of compost extracts on seed germination and root growth, providing a reliable assessment of compost quality. Local agricultural seeds such as **Mung Bean (*Vigna radiata*)** and **Mustard (*Brassica nigra*)** are commonly used due to their rapid germination and high sensitivity to phytotoxic compounds.

The assay evaluates both **seed germination** and **root elongation**, integrating these parameters into a single Germination Index (GI%). Immature compost containing ammonia, organic acids, phenolic compounds, or excess salts inhibits seed growth, resulting in lower GI values. In contrast, mature compost promotes normal germination and root development. Generally, a **GI ≥80%** indicates mature, non-phytotoxic compost suitable for agricultural application, whereas lower values suggest incomplete stabilization and the presence of phytotoxic substances. Therefore, the GI assay serves as a simple, rapid, and cost-effective method for confirming the biological safety and agronomic suitability of compost.

6. CONCLUSION

Strategic Recommendations for Vellalore

The Phase-II biomining project at the Vellalore Dump Yard can be significantly optimized by shifting from a purely mechanical viewpoint to an advanced Bioprocess Engineering approach. Based on globally compiled research data, the following three immediate recommendations are laid out for the Coimbatore City Municipal Corporation (CCMC):

1. **Mandatory Microbial Pre-treatment:** Implement a 72-hour *Lactobacillus plantarum* spray stage on all freshly formed windrows prior to mechanical handling to eliminate the neighborhood odor crisis and vector breeding immediately.

2. **Enzymatic Bio-Drying:** Leverage *Bacillus* and *Aspergillus* enzymatic hydrolysis loops to dry out the legacy mass below 25% moisture. This stops the creation of hazardous groundwater leachate and prevents trommel clogging, increasing

mechanical throughput to the desired 1,500 TPD target.

3. **Standardized Ecotoxicological Screening:** Move away from unchecked distribution of recovered earth. Establish an on-site testing protocol utilizing AAS and Germination Index assays to verify heavy metal immobilization, creating a premium, safe, and commercially viable "Bio-Earth" product line.

Ultimately, these interventions will support the transformation of Vellalore from an environmentally degraded dumpsite into a model circular economy resource recovery facility, providing insights applicable to landfill remediation projects throughout the developing world.

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