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Feasibility of Characterization and Utilization of Landfill Mined Soil Like Fractions (LFMSF) of old MSW dumps for Sustainable Development: A Critical Review

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Abstract: *Unscientifically Created Landfills and dumpsites possess a severe threat to geo environment due to uncontrolled release of greenhouse gases and toxic leachate, accidental fires and occasional slope failure. Further, these sites also become a socio-economic burden on the municipalities through the consumption of enormous land of the modern day cities and creation of unhealthy living conditions for the surrounding populace. However, an increase in demand for the land to settle the ever growing population of such cities and to meet the infrastructural requirements the habitable boundaries of these cities are expanding and hence mining of the UCLDs termed as landfill mining LFM being advocated. Apart from this LFM facilitates the recovery of resources such as metals, plastics, glass and paper from the landfill mined residues, LMRs. Despite these advantages, LFM faces a significant challenge due to the creation of huge volumes of fine-fractions, separated from the LMRs, also known as 'Landfill-Mined-Soil-like-Fractions', LFMSF, which primarily is a conglomeration of organics, soils, debris and smaller chips of metals, plastics, and glass. Unfortunately, utilization of the LFMSF, as a manmade resource, has still not become a well-accepted practice. This is mainly due to the lack of understanding of the characteristics of the LFMSF that are mostly site-specific. With this in view, synthesis of the literature dealing with the issues related to the characterization and utilization of the LFMSF conducted. It realized that by developing and following adequate characterization protocols and guidelines, the LFMSF be utilized as a manmade resource for sustainable development, without affecting the geo environment.*

Keywords: Landfill Mining (LFM), Landfill Mined Soil-like Fraction (LFMSF), Waste Characterization, Sustainable Waste Management, Resource Recovery, Geotechnical Applications

I. INTRODUCTION

Worldwide waste generation has been steadily increasing due to rapid urbanization, industrialization, and population growth. According to recent estimates, the world generates over 2 billion tonnes of municipal solid waste annually, with this figure expected to rise significantly in the coming decades. The United States is the highest waste-generating country, producing over 250 million tonnes of waste per year. Other major contributors include China, India, Brazil, and Indonesia, driven by their large populations and expanding economies. High-income countries typically generate more waste per capita, while developing nations face challenges in waste management infrastructure, leading to environmental and health concerns globally as per the data from World Bank and the United Nations Environment Programme (UNEP).. In developing countries, the accumulation of large quantities of waste in open dumps over the past tens of years has resulted in such dumps occupying vast areas of land and reaching heights as tall as 50 m or more. Statistics shows that around 30–40 million tons of municipal solid waste is disposed in dumpsites annually in India

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(Downtoearth, 2019). Table 1 shows the amounts of municipal solid waste generation over the last three decades (1990–2023) for the top five waste-generating countries.

It shows a clear trend of increasing waste production, especially in rapidly developing nations like China and India, while already industrialized countries like the United States continue to generate the highest volumes.

Table 1. Municipal solid waste generation over the last three decades (1990–2023)

Rank	Country	Annual Waste Generation (Million Tonnes)	Per Capita Generation (kg/day)	Reasons
1	United States	~265 million	2.58	High per capita waste; major contributor of plastics and food waste
2	China	~235 million	1.02	Rapid urbanization; growing e-waste concern
3	India	~160 million	0.45	High organic content; poor segregation rates
4	Brazil	~80 million	1.05	Low recycling rate; large informal sector
5	Indonesia	~65 million	0.75	Marine plastic pollution hotspot

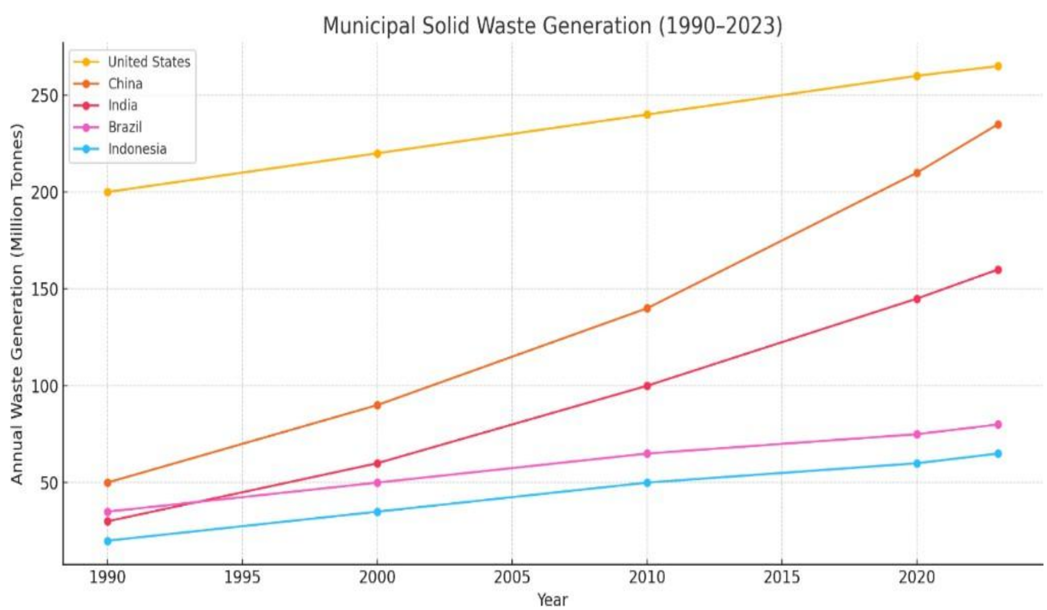

Fig.1. Municipal solid waste generation over the last three decades (1990–2023)

Landfills have long been considered as a way to store waste at minimum cost. Today it is well known that this kind of waste disposal shows a series of problems related to possible contaminations caused by the degradation of organic waste, which generates methane emissions that contribute to global warming [21]. Old dumpsites, without any sort of protection for reducing emissions, are a source of local pollution due to the leaching of hazardous substances [19]. Legacy dumpsites are repositories of heterogeneous, decomposing waste often managed with limited environmental safeguards [1], [9]. As cities urbanize, the demand for land and the impact of dumpsite pollution necessitate interventions like landfill mining (LFM) a strategy adopted in India, China, and the EU [3], [12]. LFM not only recovers land but also generates secondary raw materials like plastics, metals, combustibles, and a dominant fraction of soil-like fines (LFMSF) [35]. Table 2 shows the countries with the largest number of dumpsites or unmanaged landfill sites based on data compiled from sources like the Global Waste Management Outlook (UNEP), Waste Atlas, and national waste reports.

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Table 2. Countries with the largest number of dumpsites or unmanaged landfill sites

Rank	Country	Estimated No. of Dumpsites	Key Characteristics
1	India	~3,000+	Majority are legacy open dumpsites; poor segregation and coverage
2	Indonesia	~1,800	Many large urban dumpsites; marine plastic leakage hotspot
3	Brazil	~1,600	Mix of official landfills and illegal open dumps
4	Nigeria	~1,200	Minimal regulation; health risks from open burning
5	China	~1,000+ (declining)	Many closed post-2010; replaced by engineered landfills
6	Bangladesh	~950	Uncontrolled disposal in urban peripheries
7	Pakistan	~850	Open dumping common; informal sector active
8	Mexico	~800	Transitioning to sanitary landfills; dumpsites still active
9	Philippines	~750	Major accidents (e.g., Payatas); ongoing shift to sanitary sites
10	Democratic Republic of Congo (DRC)	~700	Often within city limits; poor leachate control
11	Ethiopia	~500	Major incident in 2017 (Koshe); weak landfill regulations
12	Vietnam	~450	Urban-rural disparity in waste management
13	South Africa	~420	Many municipal dumps still in use
14	Thailand	~400	Illegal dumping and seasonal fires are common
15	Kenya	~350	Dandora dump in Nairobi among the largest in Africa

II. ENVIRONMENTAL AND HEALTH HAZARDS ASSOCIATED WITH LEGACY WASTE DUMPSITES

1. Open dumpsites or unscientific landfills are deemed to be closed when the landfill reaches an unstable height and additional dumping of waste can lead to landslides. Earlier, disposal of non-segregated waste in unscientific landfills used to be the norm. But unlined unscientific dumpsites produce toxic leachate that forms puddles in the surrounding area and seeps into the ground, polluting both surfacewater and groundwater resources. Such dumpsites also release greenhouse gases like methane. They are prone to dumpsite surface fires that result in rapid emission of dangerous pollutants into the atmosphere. Unscientific dumpsites also put limitations on urban development. These and other negative effects have made disposal of waste in unscientificdumpsites

untenable practice. On the other hand, robust promotion of better waste-management practices like source segregation and the three Rs (reduce, reuse and recycle) has created the conditions for a paradigm shift in waste management. Old landfills and their legacy waste need to be dealt with if the shift in waste management is to succeed. Table 3 shows the data related to the disasters caused by the open dumpsites and unmanaged sites. The common causes of disaster are overloading and height violation, uncontrolled methane gas buildup, lack of leachate and storm water control, poor waste segregation and inadequate management practices. Heavy metal leaching into groundwater is a serious concern [33]. Unpleasant odor, dust, and bioaerosol emissions occur during excavation and handling [8]. Greenhouse gas generation, especially methane, from anaerobic degradation must be managed [14]. Proper stabilization and monitoring can reduce these impacts. Leachate testing (TCLP, SPLP) is essential before any reuse [33].

Table 3. Disaster caused by dumpsites or unmanaged landfill sites

S. No.	Location	Year	Cause	Impact	Lessons Learned
1	Payatas, Manila, Philippines	2000	Heavy rainfall caused slope failure of an open dumpsite	~300 deaths; major landslide; hundreds displaced	Need for landfill closure, slope stabilization, and better drainage
2	Leuwigajah, Bandung,	2005	Methane gas explosion and waste collapse triggered by	~143 deaths; 2 villages buried	Importance of gas management, landfill zoning,

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	Indonesia		rain		and early warning
3	Koshe Dump, Addis Ababa, Ethiopia	2017	Waste pile collapse after new dumping on old waste	~115 deaths; major public outcry	Regular monitoring, buffer zones, and regulated dumping essential
4	Ghazipur Landfill, Delhi, India	2017	Rain-induced slope failure; overloading of waste	2 deaths; traffic disruption; serious environmental alarm	Urgent need for height regulation, waste diversion, and capping
5	Quezon City, Philippines (Smokey Mountain)	1990s–2000s	Fires, gas buildup, and poor management in dumpsite	Dozens of lives lost over years; public health crises	Phasing out of open dumpsites, improved waste segregation
6	Kumbakonam, Tamil Nadu, India	2020	Fire outbreak in mixed-waste dump site	Air pollution; damage to nearby property	Need for source segregation, fire control measures
7	Deonar, Mumbai, India	Recurring (2016, 2018)	Frequent fires due to methane buildup	Toxic smog over Mumbai; health concerns	Gas capture systems and timely closure plans
8	Stocznia, Poland	1992	Illegal dumping and lack of waste compaction	Explosion and fire; contamination of surrounding land	Proper regulation of industrial landfill sites
10	Avalon Landfill, Canada	1998	Leachate overflow due to improper lining	River pollution and legal liabilities	Strict enforcement of landfill design standards

III. COMPOSITION AND CHARACTERISTICS OF LFMSF

LFMSF consists primarily of decomposed organic matter, sand, silt, inert fractions, residual plastics, glass, ash, pathogens, and heavy metals [23], [42]. Its proportion ranges from 30% to 70% of mined material depending on landfill age and climatic conditions [10], [23].

Table 4. Legacy waste composition

Sr. No	Dumpsite	Composition (% by weight)
1	Kolkata – Dhapa Banerjee et al. (2022), *Probabilistic Resource Recovery…*, JIAEM	Also from 100 kg sample: non-combustibles 25–30 %, combustibles 10–15 %, recyclables 1–2 %, bio-earth 15–20 %, coarse organics 20–30 %, rejects 5–10 %, moisture 15–25 %)
2	Delhi – Bhalswa Express/field investigations & Wikipedia summarizing peer-reviewed groundwater studies	~ 800 million kg legacy waste; landfill height ~ 60 m; confirmed heavy-metal contamination (Cd, Zn, Cu) in groundwater and soil
3	Delhi – Three sites (Bhalswa, Okhla, Ghazipur)	Fine-fraction (“fines”): ~ 72 %; stones/inert: ~ 23 %; combustible/polymeric: ~ 4 %; miscellaneous: ~ 1 %
4	Older dumpsites (Delhi, Hyderabad) CSE report in *Down To Earth* (2022)	Fine (> 75 %) indicating aged and heavily degraded organic content; carbon content low (3–9 %)

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IV. PHYSICAL, CHEMICAL, AND BIOLOGICAL CHARACTERIZATION

1. Physical Properties: Grain size: 60–80% silt and fine sand fractions [17]. Moisture content: 20–50% depending on depth and compaction [24]. Bulk density: 1.1–1.6 g/cm³; porosity ranges between 30–45% [28].

2. Chemical Properties: pH: Neutral to slightly alkaline (6.5–8.5), influenced by ash and lime content [15]. LOI (Loss on Ignition): Indicative of organic content; ranges from 10–30% [13]. Heavy metals: Commonly found—Pb, Cd, Zn, and Cr may exceed safe soil limits [33], [26]. Calcium carbonate ($CaCO_3$) presence increases over time due to mineralization [5].

3. Biological Aspects: Pathogen load reduces with time; fresh LFMSF may contain E. coli, Salmonella, and helminths [20]. Bio-stabilization techniques such as aerobic composting, vermicomposting, and anaerobic digestion can enhance stability [5], [7].

Historically underutilized, LFMSF now presents opportunities for circular resource recovery, particularly if its geotechnical, chemical, and biological properties are well understood and risks mitigated [6], [21]. A sustainable alternative often advocated by different researchers to reduce the footprint of old waste dumps is through landfill mining, thereby reducing the height and area occupied by the old waste and creating space for placing additional waste [37][23]. A landfill needs to be at least 15 years old before planning mining activities [18]. The first reported case of landfill mining historically is at the Hirya landfill, Israel in 1953 with the objective of obtaining fertilizers for orchards [7][43]. In last 30 years, more than 60 landfill-mining projects have been attempted [51]. The main products of landfill mining after segregation are: (a) oversized stones, debris, and coarse gravel (>50 mm), (b) combustible material (plastic, textile, wood etc.), (c) recyclable material (metal, glass etc.), and (d) soil-like material. Soil-like material (SLM) is the largest product obtained from landfill mining and its re-use is one of the major factors to justify the economic viability of mining projects. The main re-use for SLM has been reported in on-site applications as daily/final cover material at the site itself [3],[11],[23]. There is no universally adopted definition of 'soil-like material' and it is usually defined based on the size of screens adopted by different researchers. SLM is observed to be usually 40–80 % of the total materials mined from the landfills [40]. The high content of SLM in the aged MSW may be due to the deposition of drain silts, street sweepings, construction and demolition waste atthe landfill site. The daily soil cover along with the degradation of biodegradable matter available in the MSW also contributes to high soil-like content [51]. Studies on using SLM in off-site applications (earth-fills, compost etc.) are summarized hereafter. Several investigators have reported studies on the re-use of SLM as earth-fill both in on-site applications and off-site applications. Heavy metals as major contaminants in SLM [13],[18],[43], thus limiting its use in offsite applications. However, use of SLM for off-site applications in roads and in embankments after washing and blending [28]. Geotechnical properties of SLM have been studied by [20],[34].

The strength properties have been found acceptable by all except [17]who reported a reduction in strength with an increase in organic content. Concerns regarding long-term settlements due to high organic content have been indicated [39]. Large scale use of SLM as earth-fill in off-site applications has not been widely reported. Table 4 shows the intensive study on research so far done on dumpsites or unmanaged landfill sites and the details of projects conducted

Table 5. Studies taken worldwide on dumpsites or unmanaged landfill sites to calculate reuse potential

S. No.	Study	Country	Year	Duration	Procedure	Remark
1	**The Waste Crisis – Book Reference** Tammemagi, R.: *The Waste Crisis*. Oxford Univ. Press (1999).	USA	1999	—	Comprehensive review of landfill & incinerator impacts	Early awareness of sustainable waste practices
2	**Life-Cycle Inventory Study** Komilis, I., Ham, R.: *J. Env. Engg.* **129(10)**, 956–963 (2003).	USA	2003	1 year	LCA of MSW processing and uncertainty estimation	Groundwork for future landfill LCA models

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3	**Methane Estimation from MSW** Zhang, L. et al.: *J. Hazard. Mater.* **152(2)**, 720–724 (2008).	China	2008	1 year	Measured methane emissions from landfills	Supported need for gas capture & control
4	**Biological Treatment of LFMSF** Komilis, D. et al.: *Waste Manage. Res.* **28(5)**, 440–449 (2010).	Greece	2010	1 year	Studied composting and stabilization of fines	Fines can be treated biologically
5	**Landfill Mining Review** Krook, J. et al.: *Waste Manage.* **32(3)**, 513–520 (2012).	Sweden	2012	2 years	Meta-analysis of 20 years of LFM research	Identified research gaps & value streams
6	**REMO Project** REMO Project Team: *J. Cleaner Prod.* **129**, 681–690 (2016).	Belgium	2016	3 years	ELFM, LCA, MFA, recovery integration	Model for ELFM success
7	**Italy Waste Characterization**	Italy	2016	1 year	Excavation & testing of old waste	Highlighted heterogeneity
	Cossu, R., Motzo, R.: *Waste Manage.* **49**, 1–2 (2016).					
8	**Solid Waste Rules – India** MoEFCC: *SWM Rules*, Govt. of India (2016).	India	2016	—	Framed policy for waste processing	Enabled legacy waste treatment legally
9	**Enhanced Landfill Mining Policy** REMO Final Report, Belgium (2016).	Belgium	2016	2 years	ELFM review and potential pathways	Supported EU circular goals
10	**Fresh Kills Park** NYC Dept. of Sanitation (2020).	USA	2020	10+ years	Capped landfill converted into green park	Global reuse model
11	**Bangalore Bellahalli** KSPCB Report (2020).	India	2020	1 year	Gas/leachate monitoring in biomining	GHG emissions reduced
12	**Surat Legacy Project** Surat Municipal Report (2020).	India	2020	2 years	RDF + composting from trommel waste	70% waste diverted
13	**Jawahar Nagar, Hyderabad** TSPCB Circular (2020).	India	2020	2 years	Trommel + composting operations	High RDF & compost output
14	**Pune LFM Trial** PMC Reports (2020).	India	2020	1 year	Reuse of inert in construction	Proven road fill reuse
15	**Ghazipur Landfill Mining** CPCB & MoHUA (2021).	India	2021	3 years	Trommeling, RDF, sorting	Waste reduced, emissions a concern
16	**Kolkata Dhapa Site** KMC Soil Division (2021).	India	2021	1 year	Landscaping with LFMSF	Vegetation improved
17	**Bhopal Bhanpur Project** MPPCB Report (2021).	India	2021	1 year	Eco-brick from LFMSF	Passed structural tests
18	**Indore Biomining** GIZ India (2021).	India	2021	2 years	Biological + mechanical separation	Land reclaimed for development
19	**Lucknow Green Space Reuse**	India	2021	2 years	Post-biomining green park	Converted dumpsite

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	LMC Report (2021).					into public area
20	**Jabalpur LFMSF Subgrades** Awasthi & Yadav: *Transportation Geotechnics* **37**, 100768 (2023).	India	2023	1 year	CBR testing, road fill application	Found suitable for low-traffic roads
16	**Kolkata Dhapa Site** KMC Soil Division (2021).	India	2021	1 year	Landscaping with LFMSF	Vegetation improved
17	**Bhopal Bhanpur Project** MPPCB Report (2021).	India	2021	1 year	Eco-brick from LFMSF	Passed structural tests
18	**Indore Biomining** GIZ India (2021).	India	2021	2 years	Biological + mechanical separation	Land reclaimed for development

V. REUSE POTENTIAL AND APPLICATIONS OF LFMSF

1. Civil Engineering: Landfill final cover systems and daily intermediate cover [16]. Subgrade material for low-volume roads after stabilization [32]. Eco-bricks: Combined with fly ash or cement [34], [13]. Soil replacement in mine backfilling and embankments [20]. Table 4 shows the Studies taken worldwide on dumpsites or unmanaged landfill sites to calculate reuse potential
2. Agriculture and Forestry: Soil conditioner post heavy metal removal and composting [41]. Useful for energy plantations (e.g., Jatropha, bamboo) on non-food-producing lands [27].
3. Landscaping and Urban Greening: Urban buffer zones, green corridors, closed landfill greening, and bio-park development [4].
4. Energy Recovery: LFMSF with high organic content may be used in refuse-derived fuel (RDF) manufacturing, though calorific value is low (~8–10 MJ/kg) [11].

VI. GLOBAL CASE STUDIES AND BEST PRACTICES

Belgium (REMO project): LFMSF used in subgrade layers after cement stabilization [30], [31]. USA (Fresh Kills Landfill, NY): LFMSF incorporated in slope stabilization and landscaping [22]. India: Cities like Delhi, Pune, and Hyderabad struggle with LFMSF reuse due to lack of reuse protocols and guidelines [8].

VII. CHALLENGES

Regulatory gaps: Most countries lack standards for LFMSF reuse [18]. Public perception: Resistance to using “waste-based” materials [38]. Variable quality: Composition varies drastically even within the same site [26]. Economic feasibility: High costs of processing, transportation, and testing [2].

VIII. RECOMMENDATIONS AND RESEARCH GAPS

Standardize LFMSF classification and testing protocols (e.g., geotechnical, TCLP, EC). Promote low-cost stabilization using biochar, lime, or industrial by-products. Develop policy frameworks for LFMSF reuse through MoHUA, CPCB, or state-level agencies. Encourage field trials, academic collaborations, and PPP models for implementation.

IX. CONCLUSION

LFMSF presents both a challenge and an opportunity. With growing environmental awareness, there is an urgent need to treat and utilize LFMSF through sustainable, scientifically validated methods. Its reuse aligns with United Nations SDGs, especially SDG 11 (Sustainable Cities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). With proper regulations, public-private collaboration, and awareness, LFMSF can be a resource, not a liability.

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