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Rehabilitation of Legacy Landfills in Constrained Megacities: A Retrospection

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ABSTRACT

Unscientifically created landfills/dumpsites and engineered landfills, which occupy vast precious land, have become an integral part of modern-day megacities. Improper management of these facilities often harms the geoenvironment owing to the release of landfill gases and leachates laden with heavy metals and emerging pollutants, structural failures, and occasional fires, causing a severe threat to the nearby population. One of the ways to get rid of this menace is to reclaim the land by resorting to landfill mining (LFM). However, utilization of the residues generated from LFM, known as landfill-mined residues (LMRs), is not often techno-commercially feasible due to their composition and logistic constraints. Under these circumstances, another viable solution would be to rehabilitate such entities by developing green patches and recreation facilities, keeping in view their structural stability. Such a philosophy would assist the urban local bodies facing the space crunch to improve the aesthetics and ambiance of these grey spots of the metropolis. However, in both cases, it would be necessary to assess the state of the waste in these entities by conducting a series of invasive (by characterizing the retrieved samples) and non-invasive geophysical investigations to find out the most technically feasible solution. Under these circumstances, the biggest question that present-day researchers and policymakers face is the accuracy and reliability of the outcomes of these investigations for MSW, which is significantly heterogeneous in nature. This necessitates discussion among the scientific community regarding the pros and cons of the said rehabilitation pathways and investigations that include the interpretation of the results obtained.

Keywords: constrained megacities, landfills, closure, invasive and non-invasive investigations, rehabilitation, infrastructure development.

NOMENCLATURE

C&D	Construction and demolition	ELF	Engineered landfill
ERT	Electrical resistivity tomography	EM	Electromagnetic
LFM	Landfill mining	GPR	Ground penetrating radar
LMRs	Landfill mined residues	LFMSF	Landfill mined soil like fractions
MSW	Municipal solid waste	MASW	Multichannel analysis of surface waves
RDF	Refuse derived fuel	OM	Organic matter
R_w	Electrical resistivity of liquid medium	R_b	Bulk electrical resistivity
V_s	Shear wave velocity	UCLDs	Unscientifically created landfill/dumpsites
θ	Volumetric moisture content	*w*	Gravimetric moisture content

1 INTRODUCTION

Disposal of municipal solid waste (MSW) into unscientifically created landfills/dumpsites (UCLDs) and engineered landfills, hereafter designated as landfills, is preferred worldwide. This primarily can be attributed to the techno-commercial limitations associated with the existing MSW treatment pathways

(Goli et al., 2021) and mechanical recycling techniques (Goli et al., 2020; Goli & Singh, 2021). However, these landfills, especially when they are UCLDs, have also been recognized as a major threat to the geoenvironment owing to the foul odor, emission of greenhouse gases (viz., CO_2, CH_4, and H_2S), generation of toxic leachate with emerging contaminants and heavy metals, fire incidents and occasional slope failures (Chandana et al., 2021; Krook et al., 2012). Moreover, as per the data in Table 1, the countries have many legacy landfills with no pollution prevention or monitoring schemes. Under these circumstances, rehabilitation of landfills by restoring soil health, flora, and fauna is considered a panacea. This can be achieved either through displacing the complete waste mass from its current location through landfill mining (LFM) or as it is by utilizing the top surface of the closed landfill for infrastructure development. In this context, LFM has gained momentum among the mentioned schemes due to its wide advantages, which includes:

- Land creation for settlement of the populace or infrastructure development (Mandpe et al., 2019).
- Prevent contamination of the geoenvironment from landfill gas emissions and release of leachate.
- Creation of land for future waste disposal/management activities.
- Valorization of secondary resources, read as landfill-mined residues (LMRs) such as glass, metals, plastics, wood, stones, refuse-derived fuel, landfill-mined-soil-like fractions (LFMSF), etc., in various applications (Goli et al., 2022b).

Table 1. *Summary of country-wise data on the landfills.*

Reference	Country	Number of landfills	Key points
Kaczala et al. (2017); Lee et al. (2020)	China	1000 legacy landfills	>2000 UCLDs
Nicholls et al. (2021)	Germany	68,000	1027 are operational and the rest are closed
Monkare et al. (2016)	Finland	1,600	-
CPCB (2021)	India	3184 UCLDs 341 ELFs	UCLDs: 234 reclaimed; 8 converted to ELF ELFs: 17 exhausted 11 capped
Masi et al. (2014)	Italy	More than 10000	legacy landfills without any protection
Frändegård et al. (2015); Mönkäre et al. (2016)	Sweden	More than 6000	Mostly old and only <100 are operational
van de Sande & Rijkswaterstaat (2019)	The Netherlands	4000-6000	Mostly legacy landfills, currently 19 are operational
EPA (2022)	USA	1908	-

However, achieving all the above outcomes demands herculean efforts and incurs a huge cost. Further, the engineering performance and environmental suitability of LMRs would be the primary criteria for the utilization, without which the mined material would become a secondary waste, leading to unwanted challenges for their management. Furthermore, hesitance in accepting the LMRs and willingness to pay for them are the critical socio-economic barriers that act as a hurdle to implementing LFM projects. Therefore, landfill rehabilitation through their scientific closure and containment of the spread of contaminants in the form of leachates and gases would be a prudent idea. Such a cost-effective closure activity will create precious land that can be used for future development. However, any such attempts would require a prior condition assessment of the landfill for its biological and mechanical stability and prolonged environmental monitoring to ensure safety from an emission perspective. Previous researchers have conducted studies to assess the stability of MSW in legacy landfills through a series of invasive and non-invasive techniques, such as retrieval and characterization of decomposed MSW and geophysical investigations, respectively. Among the available geophysical techniques, electrical resistivity tomography (ERT) and multichannel analysis of surface waves (MASW) are widely popular in field applications due to their robust, simple handling and analysis nature. However, often invasive and non-invasive techniques together or individually fail to provide outcomes that can represent the entire waste mass in the landfills owing to the large heterogeneity in the deposited MSW. Also, the lack of standards necessitates repeated calibration of these instruments based on the site conditions through invasive sampling and makes these investigations unaffordable to many. In this context, this paper discusses opportunities and issues associated with (i) rehabilitating legacy landfills through LFM and infrastructure development, focusing on megacities and (ii) invasive and non-invasive techniques available for assessing waste stability in landfills.

2 LITERATURE SEARCH METHODOLOGY

A Scopus search was conducted using keywords such as landfill mining, rehabilitation, infrastructure development, geophysical investigations, landfill mined residues and MASW and ERT. The papers <10 years old were selected for review among the available publications. Keeping a large number of publications available on landfill mining, landfill mined residues and geophysical investigations in view, studies conducted from different countries were prioritized to depict the global scenario. Moreover, to the best of the authors' knowledge, the literature is devoid of technical research on the rehabilitation of landfills through infrastructure development.

3 LANDFILL REHABILITATION

3.1 Landfill mining and landfill-mined residues

Several investigations have been conducted worldwide to understand the feasibility of LFM and the utilization of LMRs for various applications. Table 2 reveals that LFMSF, which resembles soil-like material, is the dominant fraction (up to 75.2 %) of the LMRs. Hence, most studies (Datta et al., 2021; Rawat & Mohanty, 2022) have focused on utilizing LFMSF for soil amendment, structural fill materials, etc. It has also been observed that the presence of high organic matter (OM) in LFMSF is detrimental to its utilization as structural fill material, which could be the reason for no studies on the successful utilization or demonstration of LFMSF material for this purpose. Further, studies have highlighted that the leaching of heavy metals and salts from LFMSF makes them environmentally unsuitable. Despite several studies, the long-term environmental toxicity of LFMSF is yet to be established. Furthermore, most studies are feasibility analyses rather than executing LFM in a real-life scenario. This could be attributed to the fact that major landfills are often located in the suburbs of megacities, particularly in developing countries like India and China, which are heavily crowded and make the LFM activity a cumbersome task. The LMRs are generally wet when exhumed, making their drying mandatory for further processing. Unless sufficient space and energy are available, the process of LFM will be significantly impacted and delayed due to the drying of LMRs. Moreover, if the LMRs are to be transported long distances for their utilization, the greenhouse gases released during this activity will be added to the life cycle, and the process may become more detrimental to environmental safety. However, no such studies have been carried out, keeping the life cycle perspective in view. On the other hand, initiating LFM activities at a landfill that has been closed for several years (or decades) will pollute the surrounding air (release of particulate matter, volatile organic compounds and gases), subsurface (spillage of leachates) and noise (caused due to operating large vehicles and equipment). This could attract resistance from the populace, particularly if the landfills are located within densely populated areas. One of the ways to tackle this issue could be performing a thorough environmental impact assessment to identify and take the required mitigation steps. Hence, the decision on LFM as a landfill rehabilitation strategy should be taken judiciously in megacities.

3.2 Infrastructure development

Development of brownfield projects: (i) recreational facilities such as water parks, museums, exhibition grounds, golf courses, ski resorts and sports complexes (Gliniak & Sobczyk, 2016; Koda et al., 2022) and (ii) solar parks on the legacy landfills have been carried out in the past. Especially, the development of solar parks on the top of legacy landfills recently became popular in the USA. In 2021, local governments across the USA announced 21 projects that could combine and produce 207 MW of energy (Barone, 2022). This decision could be majorly driven by the successful conversion of erstwhile landfills in Kings Park [Long Island, New York] (Pickerel, 2019), Combe Fill North [Mount Olive, New Jersey] (Lewis, 2022), Spanish Fork [Utah] (Lombardo, 2021) and Anne Arundel County [Annapolis, Maryland] (DoP, 2022) into solar parks. Similarly, a golf course was created on a legacy landfill in Trinity Forest [Dallas, US] (Loomis, 2018). Incidentally, most projects developed do not impose extreme structural loads on the waste mass. Therefore, settlement induced due to mechanical loads is negligible if the landfills are stable for biodegradation. However, creep-induced settlements might still play a major role when infrastructure is developed immediately or in the early stages of landfill closure. Hence, quantification of creep-induced settlements is necessary.

On the other hand, in megacities of developing countries, the basic requirements are to build space to accommodate more populace, for which the development of infrastructure such as housing boards and gated communities is the need of the hour. Hence, ensuring that the legacy landfills are stable under the mechanical loads induced by these structures is yet to be studied. Keeping this in view, invasive and non-invasive investigations on establishing the stability of landfill for biodegradation and under the application of mechanical loads should be conducted.

4 INVASIVE AND NON-INVASIVE INVESTIGATIONS

Evaluating the landfill stability against the biological decomposition of MSW is of utmost importance to ensure that (i) no major accidents will occur while mining and (ii) settlements will be within the permissible limits when infrastructure is developed on the top of a legacy landfill. Moreover, such studies would also help determine the composition and utilization potential of LMRs to ascertain the economic feasibility of LFM. On the other hand, developing green patches and recreation facilities on a legacy landfill, a need of the hour for constrained megacities requires ensuring its structural and geomechanical stability. This can be accomplished most appropriately through the destructive sampling of decomposed MSW exhumed from the landfill and establishing their physicochemical characteristics in a laboratory. Mohammad et al. (2021a) have retrieved and characterized the DMSW of age between 13 and 48 months from a bioreactor landfill in India to establish the time required for biological stabilization. It was observed that the MSW in the bioreactor landfill stabilizes within 20 months. Though this activity provides first-hand information on the MSW status in landfills, they are time-consuming and create several jeopardized in surrounding environments. Hence, in-situ non-destructive (non-invasive) tests are recommended as they are cost-effective and can cover a great extent in the spatial domain (Vollprecht et al., 2019). Also, the sampling location should be decided based on the subsurface profile of the landfill (similar practice as modern-day medicos to detect ailment in bodies by CT or X-ray scan), which necessitates the in situ geophysical investigations. Gaël et al. (2017) have stated that multi-scale and multimethod geophysical survey is helpful for the rehabilitation work of landfills.

In-situ non-invasive geophysical investigations such as MASW, ERT, electromagnetic (EM) survey, ground penetrating radar (GPR) and gravity survey were performed on the landfills. These investigations help in assessing the in-situ physical properties [i.e., density, electrical resistivity, shear wave velocity (V_s), gravimetric moisture content (w) and volumetric moisture content (θ)] of the subsurface to establish its state (Balia & Littarru, 2010). The ERT (or electrical resistivity imaging) is a non-invasive geophysical technique for imaging sub-surfaces by measuring electrical resistivity at the surface with a multi-electrode system. The 2-D resistivity imaging technique is the latest state-of-the-art available to map complex geological features. Bernstone et al. (2000) studied the 2-D DC resistivity study as a pre-excavation method and stated that resistivity could be indicative of the hydraulics of landfills, including leachate pathways, saturation states, leachate pockets, etc., as the moisture content has dominated effect on resistivity. Gaël et al. (2017) also stated that ERT is suitable for moisture content determination of MSW due to their good correlation. This also helps in establishing the organic matter content and unsaturated and saturated zones, which would be helpful, at least qualitatively, to understand the requirement of drying time of LMRs. However, Bernstone et al. (2000) confirmed that no particular trend between resistivity value and material type could be established. Further, the ERT and borehole EM survey can help in estimating the moisture content in landfills over a large area only when the temperature and in-situ density represent the entire site or these parameters are known at several locations (Dumont et al., 2016). However, measuring density at different locations (both in horizontal and vertical directions) of the landfills demands retrieving the undisturbed samples, which is a daunting task, if not impossible. This is mainly due to the presence of (i) polymeric fractions such as plastics and textiles, which are fibrous, will hold the MSW matrix and provide enough resistance during sample retrieval (Goli & Singh, 2022) and/or (ii) saturated MSW matrix often collapse or compressed. Moreover, from previous findings (Aranda et al., 2021; Dumont et al., 2016; Hu et al., 2019; Zhan et al., 2019), it can be observed that the relationship between resistivity and θ, which is obtained from Archie's law (refer to Eq. 1), cannot be generalized (refer to Table 3). This is because the leachate characteristics such as salt concentrations, dissolved organic matter, and inorganic colloidal and micro(nano)plastics in the form of suspended solids (Goli et al., 2022a; Goli & Singh, 2023; Mohammad et al., 2022) that could influence the resistivity are site- and age-specific. Under these circumstances, the way out would be to develop relationships between resistivity and θ of the waste corresponding to the same landfill at different ages or locations (Neyamadpour, 2019). However, such an exercise will involve drilling several boreholes, which, apart from being a cumbersome task, is expensive too.

Table 2. *Summary of the studies on landfill mining.*

Reference	Country	Location	Age (years)	*LMR*s Composition (% w/W)	Size of LFMSF (mm)	Outcome/utilization suggested
(W. Hogland, 2002; W. Hogland et al., 2004)	Sweden	Masalycke	17-22	*LFMSF* (54.49±11.30), stones (13.70±10.02), wood (9.94±3.15), plastics (4.94±2.40), paper (9.73±7.62)	<18	<18 mm: soil improver and landfill daily soil cover material 18-50 mm: methane gas fermentation or combustion >50 mm: metal recovery, combustion, and methane gas production
		Gladsax	23-25	*LFMSF* (71.30±9.56), stones (19.10±5.10), wood (1.72±0.81), plastics (2.13±2.63), paper (2.27±0.76)		
(M. Hogland et al., 2018; Jani et al., 2016)		Hogbytorp	-	*LFMSF* (38), stones (28.07±5.39), wood (15.20±1.41), plastics (7.47±0.70), glass (5.62±1.12)	<10	*LFMSF*: redispose in landfills
		Vika	-	*LFMSF* (59), metal (2), combustible (7), excavated (22)		-
(M. Hogland et al., 2018)	Estonia	Torma	-	*LFMSF* (16), soft plastics and PET (14.9), plastics and textiles (27.1), stone (5.4), wood (5.6), glass (5.8), paper (5.7), Fe metal (2.6), unsorted > 10 mm (14.3)		-
(Somani et al., 2018)	India	Okhla, Delhi	-	*LFMSF* (71.9), C&D waste (23.4), plastics (3.3), Textiles (0.8), glass (0.2), wood (0.2)	<4.75	*LFMSF*: Landfill daily soil cover
		Jawaharnagar, Hyderabad	-	*LFMSF* (73.1), C&D waste (15.4), plastics (2.7), textiles (1.4), glass (2.6), wood (1.5)		
		Ukkayyapalli, Kadapa	-	*LFMSF* (75.2), C&D waste (16.2), plastics (3.7), textile (1.01), glass (1.73), wood (1.30)		
(Mohammad et al., 2021a)		Kanjurmarg, Mumbai	1-4	Plastics (16.3-27.8), textiles (8.9-15.7), *LFMSF* <20 mm (28.1-46.2), stones (3.5-11.2), paper (6.8-26.4), and coconut fiber (4.1-8.3)		
(Masi et al., 2014)	Italy	Lavello	-	*LFMSF* (63.6), stone (21.7), glass (11.0), metals (2.3)	<4	< 4 mm: Substitute to soil layer for cultivation of non-edible crops
(Zhou et al., 2015a, 2015b)	China	Yingchun, Hubei		*LFMSF* (75.02), stone (8.26), plastic (10.62), wood (2.43), textile (1.49), glass (0.64), metal (0.41)	<10	*LFMSF*: soil amending agent, Incineration of combustibles

Archie's law: $R = R_w \times a \times \theta^{-m}$ (1)

Where R is the bulk electrical resistivity of the matrix in Ω.m, R_w is the electrical resistivity of the liquid phase (i.e., leachate), a and m are the power law constants.

Balia & Littarru (2010) studied the feasibility of different geophysical methods as a pre-assessment study of MSW landfills reclamation and opined that seismic reflection investigations could not differentiate layers in a landfill except for its bottom. These authors have also opined that MSW is a loose and heterogenous media and inadequate for elastic wave propagation, leading to low-quality data in shallow reflection seismology. Whereas the EM survey effectively differentiates the waste and landfill bottom host formation based on resistivity difference (Gaël et al., 2017). It has been reported that MSW exhibits lesser resistivity than the host formation, which is generally consisting of either soils or rock deposits with resistivity varying from a few tens to thousands of Ω.m. Boonsakul et al. (2021) employed EM and ERT methods to find out the RDF fraction present in MSW. The resistivity is directly proportional to air-filled porosity (function of density) and inversely to the leachate content. RDF should have low conductivity and high resistivity as it has less moisture content and is less compactable than organic soil-like material. Vollprecht et al. (2019) attempted to relate the ferrous content of MSW with magnetic properties as ferromagnetic material as their magnetic susceptibility spans from 10^2 to 10^6 (in SI units), which is relatively high as compared to other components of MSW.

Though geophysical investigations are essential for landfill reclamation, they also suffer from many limitations. The major limitation of the ERT method is that it does not consider horizontal changes associated with resistivity. A more accurate way to model the subsurface would be to study two-dimensional (2-D) resistivities along the survey line. Gaël et al. (2017) reported that the conductive nature of MSW decreases the zone of interest in the case of EM and GPR techniques, and as the depth increases, the spatial resolution of these techniques also reduces. Another popularly used geophysical technique is MASW, which provides a means to determine V_s as a function of depth, providing an idea about the matrix stiffness and settlement behavior (Zekkos et al., 2014). However, due to the heterogeneous nature and state of MSW, the variation in V_s is very wide, spanning from 50 to 350 m/s (refer to Table 4) (Mohammad et al., 2021b). This is because the V_s would get influenced by (i) geomechanical properties such as confining stress, density *and* time under confinement and loading frequency and (ii) waste properties such as composition, porosity, temperature, organic matter, decomposition process, gas and leachate generation, moisture content and capillary action, etc. which are yet to be understood largely. In this context, Mohammad et al. (2021b) also opined that the instrument employed for non-destructive investigations on MSW may need to be properly calibrated as MSW is a much more heterogeneous material than soils. Unfortunately, to our knowledge, no such method is available and dedicated efforts are yet to be made in this context. Though previous researchers have developed several empirical and semi-empirical equations considering the variation in density and normal stress, the general application of these relationships is largely questionable. This is due to the variation in the waste composition among different countries, type of landfill (i.e., ELF, UCLD and bioreactor landfills), major constituents (viz., only MSW, MSW with construction and demolition waste, and so on), degradation coefficients, etc. Therefore, the calibration of these instruments with a material representative of processes that have taken place in an MSW landfill is highly questionable.

Table 3. *Relationship between R_b and θ proposed by previous researchers.*

Reference	Study Location	R_b	R_w	*A*	*m*
Ling et al. (2013)	Laboratory scale bioreactor, Beishenshu sanitary landfill, Beijing, China	$1.09\times\theta^{-1.06}$	0.41	2.66	1.06
Dumont et al. (2016)	Mont-Saint-Guibert landfill, Belgium	$0.64\times\theta^{-2.10}$	0.42	1.53	2.10
Feng et al. (2017)	Laogang Landfill, China	$0.97\times\theta^{-1.66}$	1.20	0.81	1.66
Hu et al. (2019)	Chang'an landfill, Chengdu, China (5 m depth)	$0.66\times\theta^{-1.61}$	0.76	0.87	1.61
	Chang'an landfill, Chengdu, China (10 m depth)	$0.69\times\theta^{-1.77}$	0.76	0.91	1.77
	Chang'an landfill, Chengdu, China (15 m depth)	$0.84\times\theta^{-1.87}$	0.76	1.11	1.87

Zhan et al. (2019)	Experimental bioreactor landfill, Zhejiang University, China	$1.16\times\theta^{-2.18}$	0.66	1.76	2.18
Aranda et al. (2021)	Campinas city, Southeast Brazil	$0.75\times\theta^{-2.09}$	1.03	0.73	2.09

5 CONCLUSIONS

The rehabilitation of legacy landfills can be done through either landfill mining or the development of various types of infrastructure over it. Though landfill mining results in achieving a wide range of objectives such as land creation, secondary resources generation, etc., its success will depend upon techno-socio-economical aspects such as the engineering performance and environmental suitability of the landfill-mined residues, willingness to accept the by-products from landfill mining as raw materials by the end users, generation of revenue to compensate for transportation and pre-processing costs, etc. Further, landfill mining activities might create environmental pollution and hence could attract resistance from the surrounding populace, particularly in megacities. On the other hand, legacy landfills have been used to develop facilities such as solar parks and recreational facilities that will not impart much mechanical loads over them. However, due to the extremely high population density in megacities of developing countries, it would be prudent to use these facilities to construct some green patches and recreation facilities, which would necessitate understanding the structural and biological stability of the landfill. Though invasive techniques provide information on the decomposition status and engineering properties of the decomposed municipal solid waste, they are expensive and often, it might be extremely difficult to obtain undisturbed samples by adopting them The non-invasive techniques such as ERT, MASW, EM and GPR are handy. However, they suffer due to a lack of calibration standards representative of heterogeneity and fundamental characteristics of various phases of municipal solid waste landfills. One of the ways to enhance the reliability of the outcome of these investigations will be to test the models with a large set of data generated worldwide. Further, these models should consider the age of the waste and its decomposition kinetics which would help to predict decomposition induced settlements over time. Moreover, techniques/ methodologies and guidelines/protocols that would provide information related to (i) in situ conditions of the MSW in the legacy landfills and (ii) representative properties of the decomposed MSW should be developed by the research community.

Table 4. *Shear wave velocities reported in literature for MSW.*

Reference	Location	Testing site	*Type of waste*	V_s (m/s)
Zekkos et al. (2014)	Southeast Michigan, USA	Arbor Hills, Oakland Heights, Carleton Farms and Sauk trail hills landfills	MSW	70 at the surface and 200 at a depth of 25 m
Anbazhagan et al. (2016)	Bangalore, India	Mavallipura landfill	MSW	53 at the surface, 125 at a depth of 20 m and 522 at a depth of 70 m
Aranda et al. (2019)	Campinas, Sao Paulo, Brazil	Experimental cell on Delta A landfill	MSW	58 up to a depth of 4.3 m, 75 between 4.3 and 5.8 m, 84 between 5 and 10m and 135 at 16 m
Cirone & Park (2020)	Rio de Janerio, Brazil	Landfill	MSW and Industrial waste	Ranges between 50 to 100 in the upper layers (0-7 m) and 170 and 230 at a depth of 20 m
Sarmah et al. (2022)	Japan	Four landfills in Chiba, Miyagi and Aichi prefectures	Inerts[@]	175 for Rigid waste with large content of <20 mm fraction and 95 for soft waste with fibers>20 mm fraction

Note: [@]: Inerts include plastics, glass, ceramic, concrete, rubber, metal, debris, etc.

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