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A Sustainable Approach Towards Rejuvenation of Mandur Landfill Through Biomining of Legacy Waste

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Abstract
In the past few decades, the global focus has been on modernization through the indefinite exploitation of natural resources. Worldwide rapid industrialization, advancement in technology, uncontrolled population, and unplanned urbanization have resulted in a problem in the management of waste. Waste management was never a priority and it kept on accumulating for decades. The waste in landfills has been releasing toxic gases, polluting groundwater, causing loss of biodiversity, etc., and has impacted the lives of people in surrounding areas. To mitigate the environmental impacts and bring the resources back to a circular economy, a novel and sustainable approach is landfill biomining. In this study, the legacy waste of 21 lakh tonnes from Mandur landfill is excavated, and an effective microbial consortium is sprayed at regular intervals. The sun-dried waste is segregated and screened. Recovered combustibles 25% with a calorific value of 5319 kcal/ Kg can be used for incineration or co-combustion in the cement industry while recyclables such as metals, wires (1%), etc., can be recycled. The inert such as stones recovered can be used for infrastructure or paving roads and the soil-like 36% obtained can be used as soil conditioner or for landscaping and beautification of the landfill as a park or playground. The paper also discusses the energy potential of combustibles and the technical feasibility of setting up incineration technology.

KEYWORDS
Landfill, biomining, municipal solid waste, legacy waste, recyclable.

1. INTRODUCTION

Globalization, industrialization, and population growth have forced the large-scale utilization of natural resources which has resulted in the huge generation of waste. These modernisations have also brought a lot of lifestyle changes giving rise to use and throw culture. A lot of waste, especially municipal solid waste, has been dumped on the outskirts of the cities due to unplanned urbanisation. On average every year two billion tonnes of municipal solid waste are generated across the globe and the World Bank projects that by 2050, the amount of municipal solid trash generated will reach 3.8 billion tonnes [1]. The practice of dumping of the waste tends to be the cheaper and most feasible option. Figure 1 shows the annual volume of waste disposed at the largest landfills worldwide as of 2023. But over time, this accumulated waste from so-called landfills has taken the shape of small hills and hillocks. Additionally, it is believed that 80–90% of garbage in the BRICS nations is dumped in unlined landfills [2]. Improper waste disposal contributes significantly to greenhouse gas emissions, with landfills alone responsible for about 29% of all Greenhouse gas (GHG) emissions [3]. These landfills are the breeding grounds for diseases and cause environmental nuisances such as the release of GHGs, fire incidents, groundwater contamination, mixing of leachate with freshwater bodies, odor issues, loss of biodiversity, etc. [4,5]. Even the post-care management of the closed landfill is environmentally challenging and uneconomical [6]. Every year for municipal solid waste management India loses 1200 hectares of land and 142 million tonnes of legacy waste lying at different dumpsites across 472 cities throughout the country [7,8]. The state of Karnataka is holding 173.23 lakh tonnes of legacy waste in 205 dumpsites on an estimated area of 1212.86 acres [9]. Of which Bruhat Bengaluru Mahanagara Pallike has 5 major dumpsites holding a legacy waste of 93.82 lakh tonnes occupying an area of 238 acres [9]. There is significant success in door-to-door collection by the urban local bodies but the rate of segregation a source is 78% only. The existing composting facilities are not able to handle ever-increasing municipal waste and much of the mixed waste is dumped in the landfills.

With the rise in demand, high cost of raw materials, and depleting natural resources, the storehouse of waste buried in landfills can act as an alternate resource [10]. In other words, landfills can be considered urban stocks and reservoirs for potential energy recovery [11,12,13]. Owing to the pollution abatement and the resource recovery, landfill mining is becoming popular. Landfill biomining presents a promising solution at the intersection of waste management and the circular economy. By utilizing techniques like biomining, which involves excavating legacy waste from dumpsites to recover materials for recycling or energy production, landfills can be transformed into valuable resources, thus aligning with circular economy principles of resource efficiency and reuse [14]. Figure 2 shows the global composition of the waste with the percentage of recyclables. Additionally, the utilization of landfill biogas for energy production further enhances the sustainability of landfills, contributing to the reduction of fossil fuel dependency and promoting renewable energy sources [15]. The concept of biomining not only addresses the environmental challenges posed by open dumping practices but also offers a practical and economically feasible approach to reclaiming land, reducing greenhouse gas emissions, and promoting the circular use of materials [16,17]. The synergy between landfill biomining and circular economy principles underscores the potential for innovative and sustainable waste management practices in the future.

Globally, it is the Dan Region Authority initially used the idea of biomining in 1953 at the Hiriya Landfill, which is located close to Tel Aviv, Israel to get fertilizers for orchards [18]. In India, an attempt was made to recover the compost from the decomposed waste of Deonar dumpsite near Mumbai on a pilot scale basis in 1989 [19]. The first bio-mining experiment in India was implemented in 2002–2003 in Panchvati in Nasik City, in an area of 28-acre plot with an average depth of waste ranging from 4–7 meters. At a rate of 250 g/m^3, composting bio-culture was sprayed to improve the windrow composting of old garbage. The process took 120 days and cost about 6.4 million rupees [20]. The Government of India is currently exploring funding for dumpsite bio-remediation initiatives, realizing the significance, and showing the benefits of the biomining process of recovering the old landfill or dumpsite [21].

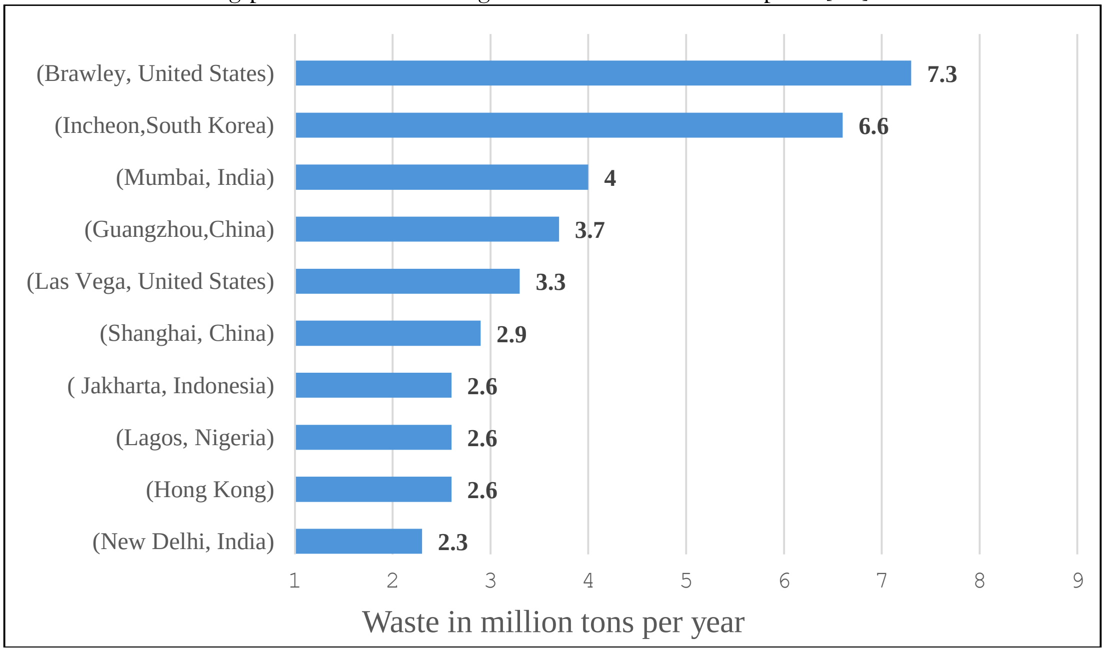


Figure 1. Annual volume of waste disposed at the largest landfills worldwide as of 2023 (in million tons) [22].

Landfill Biomining will help to achieve United Nations (UN) Sustainable Development Goals (SDG) such as SDG No.3 -*Good Health and Well-being*, SDG No.6-*Clean Water and Sanitation*, SDG No.7- *Affordable and*

Clean Energy, SDG No. 11- *Sustainable Cities and Communities*, SDG No.12- *Responsible Consumption and Production*, SDG No. 13- *Climate Action*, SDG No.15 - *Life on Land*.

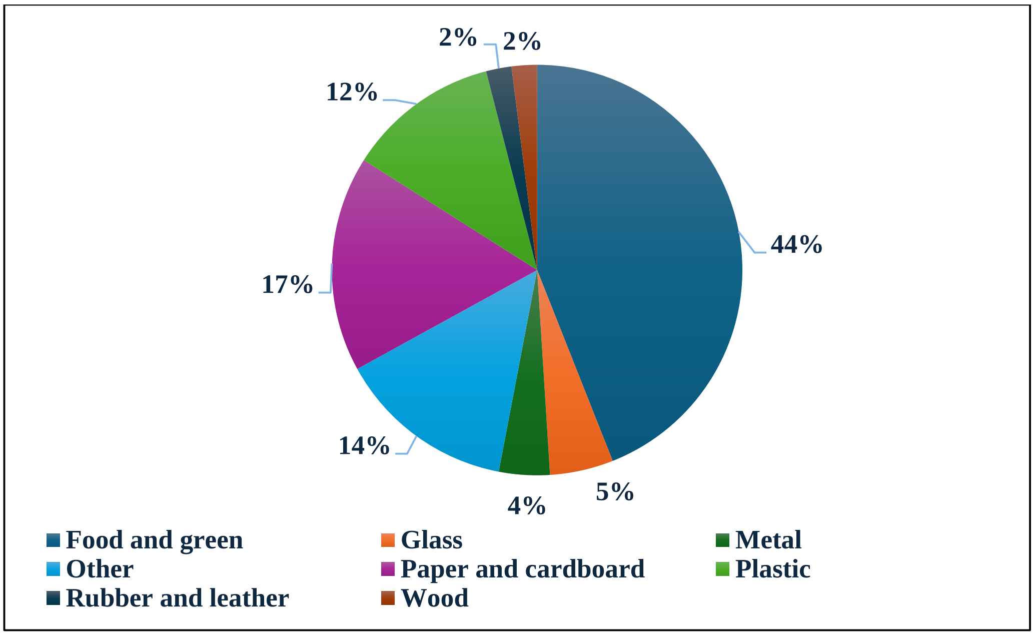
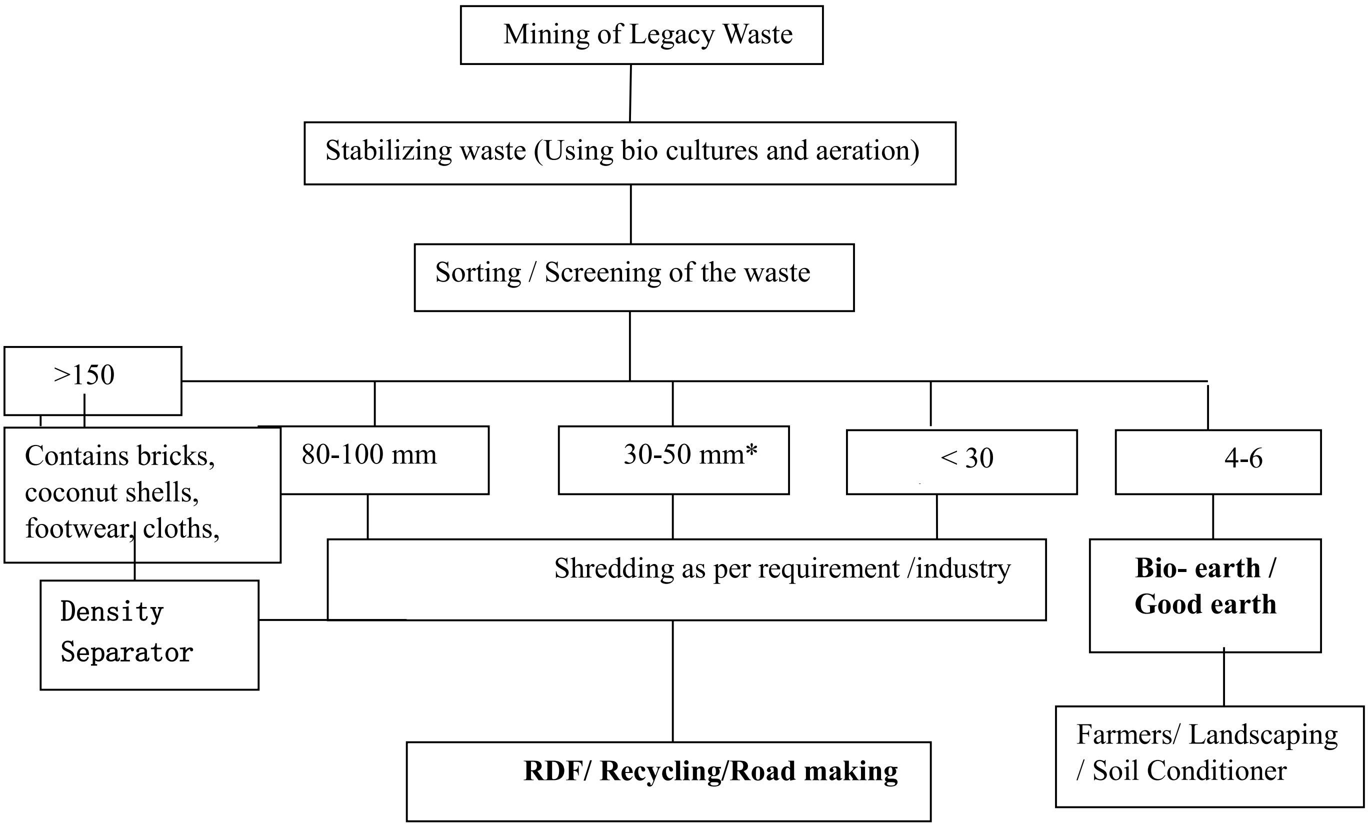


Figure 2. Graph showing the global waste composition [23]

According to the Central Pollution Control Board (CPCB) guidelines, "Biomining is the scientific process of excavation, treatment, segregation and gainful utilization of aged municipal solid waste lying in dumpsites typically referred to as legacy waste." The legacy waste is dug out and windows are made. This is done by exposing it to sun and air and sprayed with bio-culture for further composting. The stabilized waste is sorted and screened to recover the recyclables. Figure 3 presents the flow chart of the biomining process.
In the process of Landfill biomining, four steps are involved as per Central Pollution Control Board CPCB standards [5].

1. **Excavation-** During this process, windrows are made. The waste is loosened and exposed to air and sunlight which dries up the leachate in the waste letting the trash decompose later on without producing an odour. This also releases entrapped methane. The legacy waste is usually mined using an excavator or backhoe. While augers/drillers, bucket augers, and drilling rigs were used for drilling; cactus grab cranes, excavators, hydraulic excavators, and other equipment were utilized for excavation in most of the places. Based on the availability of space, equipment, and the type of waste any of these methods are followed like Tractor Tiller method, Trench Method, Cone Method, Windrow Method for Spacious Landfill Sites, or thin layer spreading Method. The heaps are laid of approx. 2m height so that it can be tilted at regular intervals [24].
2. **Stabilization-** The exposed waste is sprayed with bio-cultures (Effective microbial consortium) along with a 5% solution of cow dung to speed up the decomposition process and also the heat produced in the heap will reduce the volume by 35-40%. The heap is stabilized once there is no more production of heat, gas, or leachate, and the seeds can germinate from it.
3. **Sorting and screening-** Once the waste is stabilized waste are subjected to screening in the screen sizes 150 mm, 80 to 100 mm, 24 to 50mm, 12- 16 mm, and 4-6mm. Screens, shredders, shakers, ferrous metal separators, non-ferrous metal separators, and air separation technologies are used for processing the excavated waste [25]. The screening generally takes place after 5-6 weeks. The finest fraction is called bio-earth or good earth. It contains a mixture of humus-rich organics that improve soil fertility along with a high proportion of soil or sand.

4. **Sustainable management –** Once the segregation is done the recyclables are sent to the authorized recycling units. The stone, bricks, and ceramics were sent to the cement factory or to low-lying roads for filling and roads. The combustibles are sent for preparing refused derived fuel (RDF) for incineration or for co-combustion to generate energy in power plants and steel industries [26]. The area reclaimed will have fine fertile soil good for developing a green belt. The reclaimed land should not be used for habitation for at least 15 years as per the SWM Rules 2016, Schedule I, H (2). The reclaimed land can be used as a public park or golf course [27].



*In case of RDF (With a size upto 50 mm) shredding is not required

Figure 3. Schematic representation of Landfill Biomining [5].

2. MATERIALS AND METHOD

2.1. Study Area

Mandur Landfill is situated at Survey No.155, at Mandur village, Bidarahalli Hobli, Hoskote road Bengaluru, Karnataka. The Northen side of this landfill site is Mandur village, and the southern side is covered with lush green vegetation covering of Mandur Jyotipura forest. There are two landfill sites, adjacently located in Bengaluru East taluk, approximately 25 Km from Northeast of Bengaluru Center. Figure 4 shows the Mandur landfill in the Bengaluru Urban Map. The unscientific landfill on the North side of the Mandur Landfill site (North block) covers an area of 34.10 acres with a capacity of 650 MTPD which was under operation by M/s Organic Waste India Pvt Ltd. The second site on the South side of the Mandur Landfill site (South block) spreads over approximately 135 acres and was operated by M/s Srinivasa Gayathri & Resource Recover Pvt. Ltd. Both sites were in operation from 2005 and were closed on 1st December 2014 due to a protest from locals. Out of approx. 4,000 tonnes of waste were generated per day in Bangalore 1800 tonnes were received by this landfill for the period between 2008 to 2014 [28]. Continuous dumping has resulted in hillocks of the waste pile of 200 ft. which were bio-capped to avoid flocking of birds and dogs. The leachate generated from the landfill site showed a high contamination potential [29]. On an estimate, the landfill holds 21 lakh tonnes of legacy waste [30].

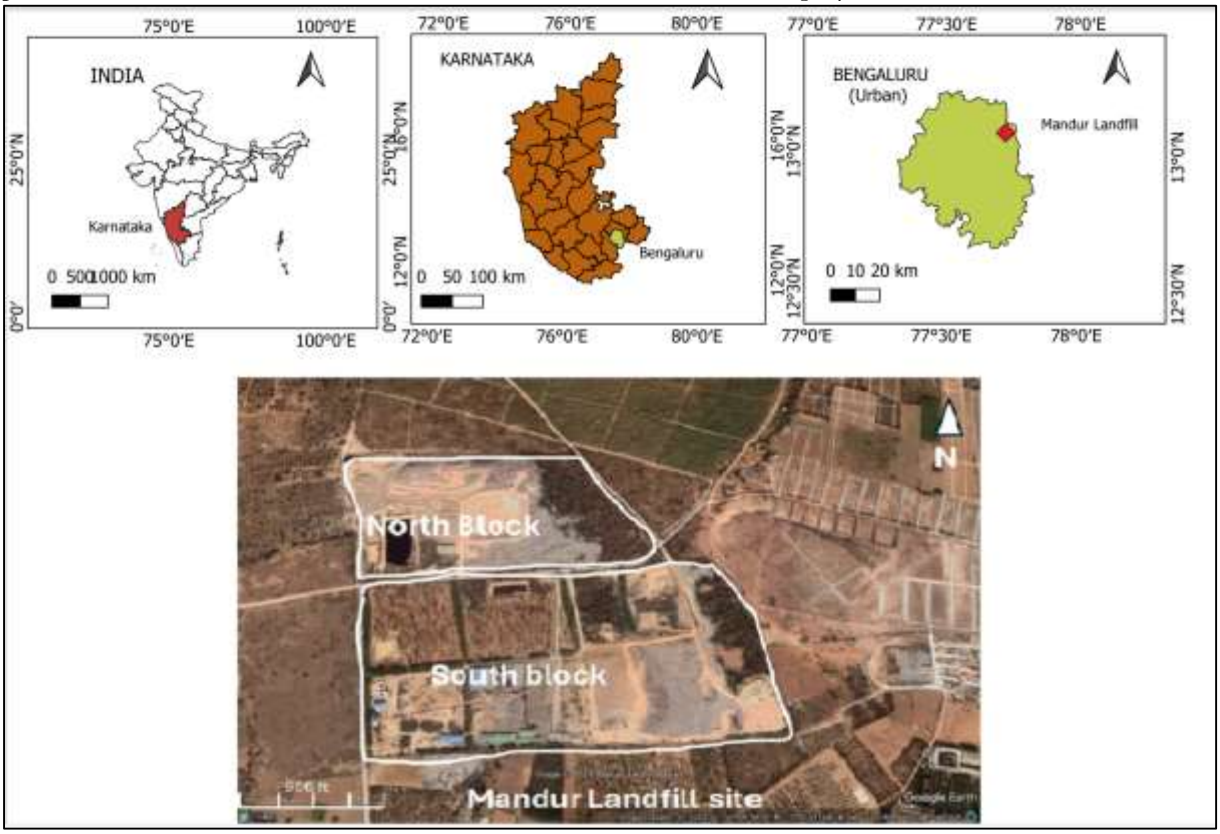


Figure 4. Map of the study area showing Mandur landfill, (Source: Satellite image from Google Earth Pro, 2024)

2. 2. Methods of Analysis

The Landfill biomining was initiated in 2023, where the heaps of legacy waste were tilled using a hydraulic excavator to make Windrows. The waste is exposed to the sun and sprayed with bio-cultures for the decomposition of any remaining organic contents. The dried waste is then fed into a trommel screen, that segregates into three fractions, i.e. Inerts (stones, metals, etc.), RDF (combustible fraction), and Bio-Earth (silt-like fine fraction) The sample collection methodology was performed as per the guidelines of American Society for Testing and Materials (ASTM) D6009–12 (Sampling Waste Piles) [31] and the number of samples was finalized as per ASTM D5321–92 (Reapproved in 2016) [32]. The representative samples were collected into air-tight zip-lock polythene bags and transferred to the laboratory for further analysis.

Initially, the samples collected were sieved through the 2 mm sieve to separate the inert material. The retained sample waste was mixed and kept in a hot air oven for 24–48 hr at 70 ± 2 °C. Dried samples were sieved and further hand-sorted to segregate the waste into different components. The components are combustibles (plastics and textiles), inorganic (ceramics, glass, and metal), inert materials (soil and stones), and others (wood, coconut shells, and bones). The weight of each component were then determined in a weigh balance and a pie chart for the physical composition of waste samples was developed. To prepare a representative combustible fraction sample, the segregated combustible components from each sampling site were mixed thoroughly. Proximity analysis was performed to determine the moisture content, volatile solids, fixed solids, and ash content following the standard procedure IS: 9235–1979 [33], IS:10158-1982 [34], and IS:1350 (Part II) -1975[35]. For the waste characterization and physicochemical study of the samples, standard methods such as Walkey and black method for Total Organic Carbon, Total Kjeldahl Nitrogen method for Total Nitrogen, Flame Photometer method for Potassium, and Stannous Chloride method for Total Phosphorous were done following the standard procedure IS:10158 -1982 [34]. The Bio-earth samples were also analyzed for heavy metals following standard procedure EN 12457-2002 [36].

2. 3. Fertilizing Index

To control the manufacturing and distribution of high-quality waste composts in India, the Fertilizer (Control) Order 1985 (FAI, 2007) established a quality control (QC) system. The poor compliance in the fertility parameters of the compost derived from city waste is due to the non-segregation of the biodegradable wastes. Compost is applied to the soil to increase soil productivity. The compost quality is determined by the indexing method [37]. To assess the utility of soil-like fraction as compost the fertilizing indexing of the analytical values is done by assigning a score value. The weighing factor is determined by the role of the parameter in improving soil productivity. The primary nutrients N, P, and K are given distinct weighing factors according to their functional significance and prevalence of deficiency in soils. The standards for allocating "score value" to analytical data & "weighing factor" to fertility parameters are indicated in Table 1. Further, the 'Fertilizing index' of the soil-like fraction is calculated using the formula:

$$\text{Fertilizing index}=\frac{\sum_{n}^{i=1} S_i W_i}{\sum_{n}^{i=1} W_i}$$

where 'Si' is the score value of the recorded value of the parameter and 'Wi' is the weighing factor of the 'i'th fertility parameter.

Table 1. Standards for allocating "score value" to analytical data & "weighing factor" to fertility parameters [37].

Fertility parameter	Score value (*Si*)					Weighing factor (*Wi*)
	5	4	3	2	1	
TOC (% dm)	>20.0	15.1–20.0	12.1–15	9.1–12	<9.1	5
TN (% dm)	>1.25	1.01–1.25	0.81–1.00	0.51–0.80	<0.51	3
TP (% dm)	>0.60	0.41–0.60	0.21–0.40	0.11–0.20	<0.11	3
TK (% dm)	>1.00	0.76–1.00	0.51–0.75	0.26–0.50	<0.26	1
C:N Ratio	<10.10	10.1–15	15.1–20	20.1–25	>25	3

TOC-Total organic carbon, TN-Total Nitrogen, TP-Total Phosphorus, TK-Total Potassium, C:N-Carbon: Nitrogen

2. 4. Clean Index

Similar to the fertilizing index, in determining the clean index the heavy metals are assigned the score values. Considering the phytotoxicity potential of the heavy metals, each heavy metal is assigned a weighing factor which is presented in Table 2 and then the clean index is calculated as per the formula:

$$\text{Clean index} = \frac{\sum_{n}^{j=1} S_j W_j}{\sum_{n}^{j=1} W_j}$$

where 'Sj' is the score value of the recorded value of the parameter and 'Wj' is the weighing factor of the 'j'th fertility parameter.

Table 2. Standards for allocating a "score value" to analytical data and a "weighing factor" to heavy metal parameters [37].

Heavy metal	Score value (*Sj*)						Weighing factor (*Wj*)
	5	4	3	2	1	0	
Zn (mg/kg dm)	<151	151–300	301–500	501–700	701–900	>900	1
Cu (mg/kg dm)	<51	51–100	101-200	201–400	401–600	>600	2
Cd (mg/kg dm)	<0.3	0.30–0.60	0.70–1.0	1.10–2.0	2.0–4.0	>4.0	5
Pb (mg/kg dm)	<51	51–100	101–150	151–250	251–400	>400	3

Ni (mg/kg dm)	<21	21–40	41–80	81–120	121–160	>160	1
Cr (mg/kg dm)	<51	51–100	101–150	151–250	251–350	>350	3

dm- dry mass, mg- milli gram, kg- kilo gram

2. 5. Grading of MSW Compost

Compost can be graded into various marketable quality categories using the criteria of fertilizing potential as fertilizing index and contamination potential as Clean index. It also gives information on the level of care needed before applying it to certain applications. The grading of MSW compost based on the Fertilizing index and Clean index and their application areas are discussed in Table 3.

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Table 3. Grading of MSW composts for their marketability and their application in different areas [37].

Class	Fertilizing index	Clean index	Quality control compliance	Remark
A	>3.5	>4.0	Complying for all heavy metal parameters	Best quality. High manurial value potential and low heavy metal content and can be used for high-value crops, like in organic farming
B	3.1–3.5	>4.0	Complying for all heavy metal parameters	Very good quality. Medium fertilizing potential and low heavy metal content
C	>3.5	3.1–4.0	Complying for all heavy metal parameters	Good quality. High fertilizing potential and medium-heavy metal content
D	3.1–3.5	3.1–4.0	Complying for all heavy metal parameters	Medium quality. Medium fertilizing potential and medium-heavy metal content
RU-1	< 3.1	–	Complying for all heavy metal parameters	Should not be allowed to market due to low fertilizing potential. However, these can be used as soil conditioners
RU-2	>3.5	>4.0	Not complying for all heavy metal parameters	Should not be allowed to market. Restricted use. Can be used for growing non-food crops. Requires periodic monitoring of soil quality if used repeatedly.
RU-3	>3.5	–	Not complying for all heavy metal parameters	Restricted use. Should not be allowed to market. Can be used only for developing lawns/gardens (with a single application), rehabilitation of degraded land

RU- Restricted Use

Further, the computation of the combustible fraction is done to determine the energy potential of the combustible fraction for the feasibility of the incineration plant and a SWOT analysis is done to justify the biomining activity in Mandur landfill.

3. RESULTS AND DISCUSSION

3. 1. Composition of Excavated Waste

Due to the unorganized dumping of non-segregated wastes, the samples were taken from different heaps by the coning and quartering method.

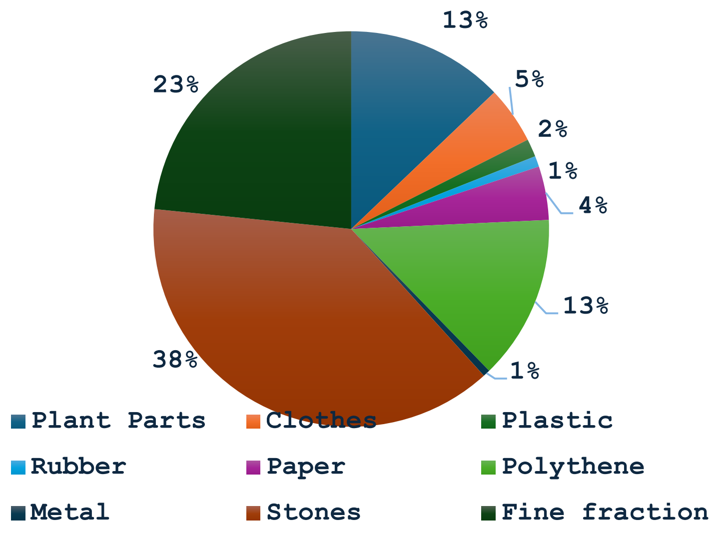

Figure 5. Graph showing the physical composition in percentage

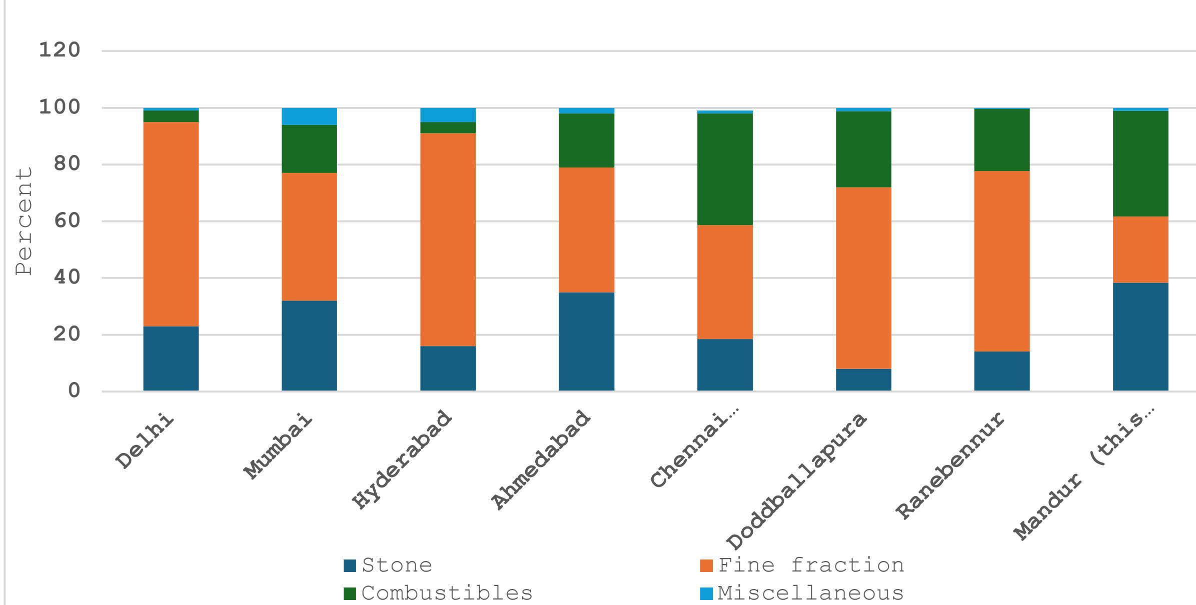

Figure 6. Graph showing the physical composition in landfills of different cities in India [38,39,40,41].

The excavated legacy waste mainly consists of inert materials (38%) like stones, pebbles, bone pieces, ceramics etc., which may be a result of capping. This can be used for landfilling and as filling material for low-lying.

The fine fraction (Bio-earth) and organic material together (36%) are enriched with nutrients and hence can be used for making compost. The other fractions such as clothes, rubber, paper, wood, polythene, etc. together (25%) are in semi-degraded form and cannot be recycled. These are combustible materials and can be used for incineration or can be burnt in a cement kiln. The metals or other hard materials (1%-2%) can be sent for recycling. The percentage of different components is presented in graphical form in Figure 5. Most Indian landfills have stones and silts as major components which are represented in Figure 6. The biomining process when compared to other cities of Karnataka such as Doddaballapura and Ranebennur, shows a high percentage of fine fractions [40 - 41]. This is due to the soil capping at regular intervals post-dumping. Figure 7 shows the tentative material balance of the physical components of excavated legacy waste and their utility.

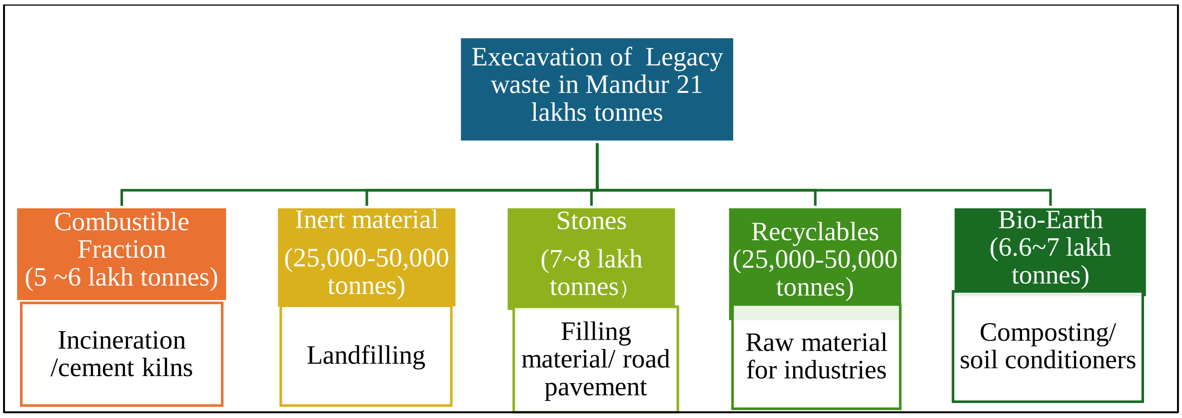

Figure 7. Material balance for the biomining in Mandur landfill.

The major output from the biomining will be the combustibles and bio-earth. Combustibles can be used for incineration or can be burnt in cement kilns and bio-earth for soil conditioning, filling material for road pavement, filling low-lying areas, etc. The recyclables especially metals are a significantly low fraction in Indian landfills, as there is an efficient informal metal collection system, which collects regularly from households and recycles the scrap metals. Because of this, the recycling industries are not in favor of the recyclables obtained from legacy wastes.

3. 2. Physicochemical Analysis

The physicochemical analysis of the Legacy Waste and Bio-earth samples shows that the colour of the samples was greyish-black and had no smell of regular compost. The moisture of Bio-earth was found to be 1.97% and that of Waste was 33.19%. The moisture is on the higher side as the sample was freshly excavated and has mixed fractions. The bulk density of Bio-earth and legacy waste was found to be 1.08 and 0.84 g/cm^3. The pH of the samples was higher than 7.5 showing that the waste is heading toward the maturation stage. The electrical conductivity was found to be below 4 dS/m for both the samples. The Organic carbon was found to be 8.29% and 8.94% which is below the Fertilizer Control Order standards. Over time the waste decomposes to release GHGs contributing to global warming, further decreasing the organic carbon levels in the landfills. The Organic matter was found to be 14.3 % for Bio-earth and 15.41% for the waste sample. Since the OC% is above 8% it cannot be used for road pavement as the maximum amount of organic matter in soil intended for use as subgrade material shall not exceed 1-3 percent as per the Indian Standard code (IRC-37-1984) [42].

The Nitrogen, Phosphorus, and Potassium (NPK) content in Bio-earth is 0.68 %, 0.057%, and 0.17 % while that of waste is 0.18%, 0.0142%, and 0.19% respectively. These values indicate that the dumped waste might lack significant amounts of organic materials rich in NPK. Landfill dynamics involving the complex nature of waste composition and decomposition processes, the NPKs in landfills are generally found to be low. The C: N ratio was found to be 12.19:1 for Bio-earth which is less than the standards and 49.67:1 for waste samples, which is very high than the standards. The total water-soluble solids (TWSS) is conducted to determine the probable solubility of the soluble components which helps in understanding the composition and the potential of its impact on the environment [43]. It was found to be 8.7 and 9.5 mg/gm for Bio-earth and waste samples. The loss of ignition (LOI) for both samples is 22.46% and 25.84% respectively (Table 4).

Table 4. Physicochemical analysis of Bio-earth and Waste samples of Mandur landfill

Fertility parameters	QC Value [44]	Bio-earth	Waste
Colour	Dark brown to black	Greyish black	Greyish black
Odour	Absence of foul odour	No smell	No smell
Moisture (% dm)	15–25	1.97	33.19
Bulk density (g/cm^3)	0.7–0.9	1.08	0.84
pH	6.5–7.5	7.55	8.1
EC (dS/m)	≤ 4	3.1	3.7
Total organic C (% dm)	≥ 16	8.29	8.94
Total N (% dm)	≥0.5	0.68	0.18
Total P (% dm)	≥0.22	0.057	0.0142
Total K (% dm)	≥ 0.83	0.17	0.19
C:N	≥ 20:1	12.19:1	49.67:1
TWSS (mg/gm)	-	8.7	9.5
Loss on Ignition %	-	22.46	25.84
Organic Matter %	-	14.3	15.41

dm- dry mass, N-Nitrogen, P-Phosphorous, K-Potassium, C-Carbon, EC-electrical conductivity, TWSS- total water-soluble solids

3. 3. Heavy Metal Analysis

The determination of heavy metal concentration is a crucial metric to prevent pollution of the soil and water resources. The presence of high polymetallic contaminants in the landfills can pose an environmental risk. In the landfill, Iron (Fe), Cadmium (Cd), Copper (Cu), Zinc (Zn), and Nickel (Ni) are the most common contaminants [45]. The heavy metals in MSW landfills end up due to the dumping of electrical items, batteries, paints, industrial wastes, etc. In this study, as presented in Table 5, the observed values are lower than the limit fixed by the Fertilizer (Control) Order 1985 (FCO), except for chromium which is 74.07mg/kg dm. The primary sources of Chromium contamination are food cans, electronic waste, and household hazardous waste, which leaches in landfills over time [46]. The Iron concentration was found to be the highest among all other heavy metals 12875 mg/kg dm. Due to its limited mobility and natural prevalence in soils, iron contamination in landfills is not regarded as harmful because it tends to remain in landfills without major migration [46].

Table.5 Heavy metal analysis of Bio-earth sample.

Heavy metal parameters	QC Value [44]	Observed values
Zn (mg/kg dm)	≤1000	333.97
Cu (mg/kg dm)	≤ 300	243.79
Cd (mg/kg dm)	≤ 5	<2.0
Pb (mg/kg dm)	≤ 100	80.74
Ni (mg/kg dm)	≤ 50	29.45
Cr (mg/kg dm)	≤ 50	74.07
As (mg/kg dm)	≤ 10	3.17
Fe (mg/kg dm)	-	12875.22

QC -Quality control, dm- dry mass, mg- milli gram, kg- kilo gram

3. 4. Indexing and Grading

The computed Fertilizing index of the analyzed Waste sample was found to be 1.4. The silt-like material (Bio-earth) fertilizing index was found to be 1. This shows that the samples are of low potential to be used as a fertilizer. The Clean index of the Bio-earth was found to be 3.0. Since the silt-like material/Bio-earth does not have enough (Fertilizing index < 3.1), it is not suitable for marketing and hence placed under Restricted Use (RU) category-1. Despite meeting the regulatory limits of heavy metals, it should not be permitted for selling due to its inferior fertilizing potential. These can be enriched to the level of good quality of compost by the addition of additives. However, these can be best suited as soil conditioners.

3. 5. Proximate Analysis of Combustible Fraction

Proximate analysis of combustible fraction helps in determining the major components such as volatile matter and fixed carbon which positively influence the calorific value while moisture and ash content have a negative impact [47]. Pre-sorting, cleaning, crushing, and drying of waste to create RDF solid fuel for incineration has shown high heat energy utilization efficiency and clean power generation [48]. In this study, the moisture content determined is 17.2 % as shown in Table 6, is quite favorable for combustion. Post-segregation from the trommel the samples were exposed to the sun, to reduce the moisture content. The volatile matter was found to be 64.3% and the ash content was 16.82%. The fixed carbon was found to be 1.58% and the calorific value was 5319 kcal/kg. The calorific value of the combustible fraction was found to be similar to sub-bituminous coal (4155 – 5708 kcal/kg) but lesser than hard black coal (5971 kcal/kg)[49]. A similar study is done on the legacy waste heaps at the Boragaon dumpsite, in North-East India [50].

Table 6. Proximate Analysis of the Combustible fraction of Mandur landfill.

MSW Characteristics	CPCB standards [51]	Observed values
Moisture %	<45%	17.2
Volatile matter %	>40%	64.3
Ash content %	<35%	16.82
Fixed Carbon %	<15%	1.58
Calorific value (kcal/kg)	>1200	5319

CPCB-Central Pollution Control Board, MSW-Municipal solid waste

3. 6. Computation of Energy Potential of the Combustible Fraction

As of May 2023, from industrial waste and MSW India can generate 5,690 MW of power but the installed capacity is 556 MW, indicating the untapped potential of WTE [52]. There is a need to focus on India's WTE projects for enhanced energy security and reduced reliance on fossil fuels.

From Figure 6 it is evident that a substantial amount of excavated waste is plastic and polythene, making recycling a complicated and costly- affair, thus waste-to- energy conversion will be more effective.

Incineration technology not only provides energy but also reduces the volume of waste by 90%.

Calorific value GCV of Mandur combustible fraction sample = **5319** kcal/kg

Converting Kcal/kg to kJ/kg = 5319 X 4.184 = 22254.7 kJ/kg

First, the heat energy generated from burning is used to calculate steam energy which is 70% of heat energy.

Steam energy available = 70% of heat energy

= (0.70 X 22254.7) kJ/kg =15,578.29 kJ/kg

The amount of heat input needed to generate one kWh of electricity is known as the heat rate.

1 kW = 3,600 kJ/h,

The conversion efficiency of power plants in India = 32.8%

Similarly, the conversion efficiency of the incineration plant = **25** %

Therefore, Heat input 3600÷ 25 = 14,400 kJ/kWh is required.

So, to produce 1kWh electrical energy 14,400 kJ of steam energy is required.

Electric power generation = Steam energy ÷ 14,400 kJ/kWh

= (15,578.29 ÷ 14,400) kWh/kg

= 1.0818 kWh/kg

Total capacity of incinerator = **600 MT/day**

Total electrical power generation = (1.0818 X 600 X1000) kWh/day = **649,080 kWh/day**
Station service allowance = 6 % of total electric power
= (0.6 X 649,080) kWh/day =38,944.8 kWh/day
Heat loss = 5 % of total electric power
= (0.5 X 649,080) kWh/day =32,454 kWh/day
Net electric power generation = Power generation – (service allowance + heat loss)
= 649,080 – (38,944.8 + 32,454) = 577,681.2 kWh/day
Net electric power generation = **577.68 MWh/day**
Converting day to hour basis = 577.68 MWh ÷ 24 h
Net electric power generated = 24.07 MW

The electric generation from Waste-to-Energy (WTE) technology in 24-hour operation can provide 17 million units (MU) monthly of electricity at least to the neighboring households. Bengaluru's daily requirement is 157 MU [53]. An incineration technology similar to the WTE plant in Bidadi, Bengaluru can be set up near Mandur landfill. Since the scope of the study is limited, a detailed economic analysis and feasibility study must be done before setting up such a project. A similar study has been done to determine the feasibility of WTE incineration in Roorkee City [54].

3. 7. SWOT Analysis

The SWOT stands for strengths, weaknesses, opportunities, and threats. The four letters make up the SWOT acronym. This analysis gives complete clarity on the objectives for the development of strategies and policies for the implementation of the project. The SWOT analysis focuses on the economic, ecological, and social sustainability perspectives of resource availability and utilization. Many researchers have done similar studies on waste management [55,56,57,58].

Table 7. SWOT analysis of the biomining of legacy waste of Mandur landfill.

STRENGTH	WEAKNESS
• Cost-effective process technology • Green compost production for sustainable agriculture • Reduction in fire incidents • Elimination of odour issues • Environmental restoration and greenhouse gas emission reduction • Improvement in air, water, and soil quality • Reduction in vector-borne diseases • Unlimited supply of raw material for bioenergy electricity generation • Sustainable move towards a circular economy • Improvement in the aesthetic value of land	• Mixed and un-segregated waste complicates the process. • Lack of policies related to recovered fractions from biomining • Limited control over quality and quantity • Complex supply chain management • High logistic costs • Activities constrained due to seasonal variation and environmental factors • Non-willingness attitude toward environmental protection and waste management • Availability of low-cost substitutes may give tough competition to recyclables.
OPPORTUNITIES	**THREATS**
• Investments and employment opportunities • Revenue from the sale of recyclables, compost, and RDF • Reduction in consumption of natural resources • Innovation and possible business models which are still under-explored.	• High capital investment and operational cost • Insufficient market for recyclables • Lack of funds for pilot projects and research • Lack of experts and technical standards • Low public-private-government partnership • Political and legislative interventions

• Reclaimed land can be used for developing integrated waste management facilities. • Business longevity and development of a strong image as environment enthusiasts • Role model and inspiration for rejuvenation of other landfills.	

4. CONCLUSION

There is no single solution for waste management, but it involves a multifaceted approach that includes segregation at the source level, reduction of waste generation, recycling, and reusing, incorporating advanced technologies to find innovative and sustainable solutions, etc. The present study highlights the importance of Landfill biomining and the benefits associated with it. The excavated waste consists of soil fraction about 36%, inert 38 %, combustibles 25%, and recyclables less than 1%. The physio-chemical analysis shows that the Bio-earth /soil-like material is not fit for fertilizer without the addition of additives but can be used as a soil conditioner. The combustible fraction has a calorific value of 5319 Kcal/kg and will be suitable for WTE incineration technology. The present study is based on a relatively small size and the seasonal variations can significantly impact the potential of the landfill biomining process which needs to be studied in detail for a comparatively longer period. Landfill biomining comes with immense opportunities for resource recovery, elimination of pollutants, and reuse of recovered land for developmental purposes.

CRediT authorship contribution statement

Neethi Nair- Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nandini N.-** Writing – review & editing, Supervision**.**

Declaration of competing interest

No conflict of interest.

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