Economic evaluation of a landfill system with gas recovery for municipal solid waste management: a case study

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Abstract: Economic activity uses resources, which leads to waste generation. With rapid industrialization and urbanization, per capita solid waste generation has increased considerably. Solid waste generation data for last two decades shows an alarming increase. Owing to its improper and untimely collection, the transport and disposal of municipal solid waste poses a severe threat to various components of the environment and also to public health. This paper describes the merits and demerits of various technological aspects of solid waste management. Landfill technology, as it is the most widely employed and is regarded as the most suitable and simple mechanism, especially for tropical countries such as India, is emphasized. All possible costs and benefits and externalities are examined. A cost–benefit analysis of a landfill system with gas recovery (LFSGR) has been carried out for Mumbai city's solid waste, accounting for certain external costs and benefits, and found that it could make a huge difference of savings of about Rs. 6.366 billion (approx. $0.140 billion) per annum with reference to the existing system of waste disposal.

Keywords: external costs and benefits, greenhouse gases, landfill, LFG, LFSGR, municipal solid waste, renewable energy, valuation.

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1 Introduction

Rapid growth of population, industrialization and urbanization results in increasing environmental pollution. The state of an economy, to a large extent, influences waste generation and municipal solid waste (MSW) in particular. In developing countries, even though the per capita waste generation is low at 300 g, changes in living conditions and the influence of western 'throw away' culture results in increased solid waste generation, leading not only to environmental degradation but also a huge loss of natural resources. Improper disposal of this waste leads to the spread of communicable diseases, causes obnoxious conditions and spoils the biosphere as a whole. On the other hand, cleanliness is another factor that influences the development of any nation that is otherwise hampered owing to improper disposal of solid waste.

The development of infrastructural facilities and disposal methods has not kept pace with the rate of waste generation, leading to increased pollution. With increasing growth rates of population, waste generation is expected to grow even faster, making the solid waste scenario much worse and a major bottleneck for development. MSW is also a significant contributor of landfill gas (LFG), which is an important greenhouse gas (GHG). In a study by Bhide (1994) it was found that landfills account for about 30% of methane emissions to the atmosphere. Hence an attempt to handle this problem of MSW management in integration with GHG mitigation and development of renewable energy sources would be a timely effort towards sustainable development.

2 Objective

With engineered sanitary landfills proved to be working well in hot climatic conditions, the development of a methodology to harvest landfill gas (LFG) from MSW would give an integrated solution for this multifaceted problem. For such a system, it is essential to carry out economic feasibility analysis by accounting for environmental as well as process externalities to assess its adaptability in developing countries such as India. In the present study, a new scheme has been proposed for MSW management with the objective of LFG recovery, and cost–benefit analysis has been carried out in a case study.

3 Present scenario of solid waste management in Indian cities

In this section, the state of the art of MSW management in India and the methods of disposal are focused on, to arrive at a scheme for the new MSW management methodology.

Dumping of waste on abandoned and derelict land is the most usual mode of solid waste disposal in India. In spite of huge budgetary and resource allocations (Table 1), MSW management has failed to keep the cities clean and hygienic, mainly owing to the poor collection efficiency, transportation, and maintenance of dumpsites. Ever-increasing rates of waste generation (Table 2) add to the already grave situation.

Table 1 Details of solid waste management in various Indian cities (source: Proc. Workshop, IIT Bombay, 1997).

City	Total population (million)	Total MSW generated (tonnes/day)	Money spent on MSW (Rs. million)	MSW workers (1000 pop'n)	Area used for LF (ha)
Mumbai	10	5000	1230	2.6	170
Calcutta	4.388	2500	18	3.0	162
Surat	2.2	1000	18	6.7	88
Solapur	0.708	300	–	1.4	15
Amaravathi	0.421	100	34	2.0	–

Table 2 Solid waste generation of various cities in India.

City	Estimated quantity of MSW generated	
	Tonnes per day	Million tonnes per year
Bombay	5000	1.825
Delhi	4600	1.679
Calcutta	3692	1.348
Madras	3124	1.140
Hyderabad	2800	1.022
Bangalore	2700	0.985
Ahmedabad	1600	0.584
Pune	1527	0.557
Kanpur	1314	0.479
Nagpur	1100	0.402
Lucknow	1043	0.381
Jaipur	1021	0.373
Surat	1000	0.365

In general, MSW management is a three-step process: collection, transportation and disposal. As is the case in many developing countries, the solid waste management system in India fails at the collection stage. Unsegregated waste creates unhygienic conditions at collection centres and also makes the retrieval of reusable material difficult.

Problems associated with MSW management in Indian cities include:

- Huge expenditure on solid waste disposal with very poor efficiency;
- Pollution due to the burning of waste;
- Unorganized and poorly coordinated transportation, resulting in excessive fuel usage and pollution generation;
- Unhygienic conditions leading to public health problems and spread of diseases;
- Loss of reusable/recyclable material due to unsegregated collection;
- Local as well as global air pollution due to the uncollected and poorly disposed waste;
- Dirty streets and cities failing to attract foreign investments and markets.

In the light of the above problems, MSW management has gained importance in recent times, and various methods of disposal have been tried. These include waste pelletization, composting, vermiculture, incineration with and without energy recovery, anaerobic digestion, biogas generation from garbage, pyrolysis and sanitary landfills. These methods include efforts to transform waste to useful or less harmful products, by means of either natural or mechanized processes. Attempts to derive fuel from waste have been made by pelletizing MSW, which are known as RDFs (Misra, 1993). This technically feasible solution for solid waste management failed on economic grounds. A similar disposal method is incineration. This capital-intensive method of waste disposal, known for its high operational costs, failed in the case of MSW for various reasons, such as pollution generation, the requirement for skilled personnel and public opposition to the installation of incinerators.

Among the methods driven by natural processes, composting has been tried extensively. Excel industries in Bombay, India, took up this practice on a commercial scale with plants in Calcutta, Delhi and Mumbai (Excel capability document, 1999). However, this method, in addition to the disadvantages that any aerobic energy-intensive system has, posed various pollution threats, such as metal poisoning of soils, as well as problems in handling it at large scale and also the disposal of the compost generated.

Vermiculture is another methodology developed for solid waste management in recent times. This practice not only converts the waste into soil but also helps to improve soil fertility. But this method has some serious limitations, which are still at the research and development level. Anaerobic digestion and biogas generation from MSW have been successfully carried out in many places, but their application is limited to very specific wastes, such as vegetable waste, slaughter wastes, market waste, etc., and also to small to medium-size reactors. These methods are very well suited for homogenous waste but not heterogeneous, as it is the case with MSW.

Though all the above methods have been tried in isolation, open pit dumping is the only predominant and large-scale disposal method in Indian cities. Engineered sanitary landfill with gas recovery has not been tried in India in spite of its proven potential as an energy generator and the prevailing favourable conditions in India. For whatever method of disposal, a new scheme of management has to be developed and tested for its feasibility in Indian conditions. In the present study, the landfill system with gas recovery (LFSGR) option has been examined, and the entire management process has been analysed for its true costs and benefits and ultimately its adaptability.

3.1 Landfill technology

In this section, the landfill technique and its sequential development are briefly described with some information from US experiences with landfills. The present situation in India is also described so as to frame the MSW management scheme and the various external costs and benefits that are to be considered in the cost–benefit analysis.

Till very recent times, landfills have been used simply to dump waste material, so not much care was taken in their construction and maintenance. But with rapid industrialization the concept has changed its shape. As uncontrolled landfills have caused pollution of various parts of the environment, and after many accidents, regulations have been imposed on landfill location, site preparation and maintenance. Some level of engineering has been made mandatory for landfills. The schematic diagram (Figure 1) shows the details of an engineered landfill. As a result of this, landfill gas (LFG) generation has increased. LFG emission to the atmosphere is a potential threat to the global environment. Hence, to avoid this danger, LFG is collected and flared. Further, because methane is a major constituent of LFG and has a considerable energy value, its use as an energy source has been evaluated. This has started the process of LFG collection and using it for various purposes.

3.1.1 Landfill gas

As waste decomposes in a landfill it produces a biogas that is approximately 45% carbon dioxide and 55% methane (STAPPA-ALAPCO-EPA, 1999). Because of the presence of methane, LFG has a heat content of about 500 British thermal units (Btu) per cubic foot, or about half that of commercially marketed natural gas (USDoE, 1998). Its Btu value depends on the composition of the waste. Typically, LFG is used for electricity generation and boiler heating.

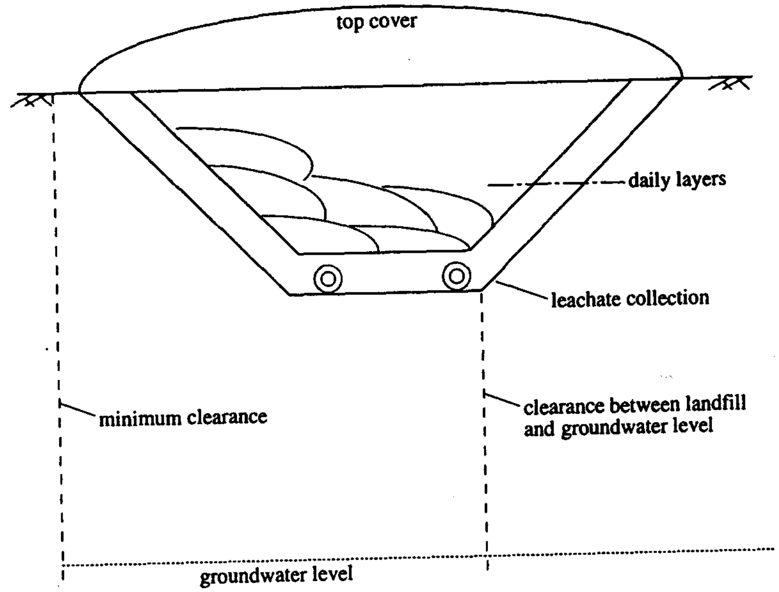


Figure 1 Details of an engineered landfill and its construction.

3.1.2 Experience in the US

It was proved that LFG could be used for electricity generation using both single and dual fuel engines. It can be used as fuel for cooking purposes and for heating boilers of various treatment systems. Effective use of LFG in countries like the US not only could provide a solution for waste management but also contribute significantly to non-renewable energy and minimize GHG emissions from MSW. In 1997, LFG contributed 952 314 thousand kilowatt hours of electricity in the US, being the next highest contributor to the renewable energy sector after hydroelectricity (USDoE, 1998). During 1993–97, among the biomass energy consumption in US, MSW and LFG contributed a significant part, of which 73% was consumed by the industrial sector (USDoE, 1999). Energy consumption supported by MSW grew from 390 trillion Btu in 1993 to 449 trillion Btu in 1997. About 80% of the projects installed for energy generation from MSW generate electricity as the sole energy product. They have a generating capacity of approximately 2600 megawatts, produced 16 million megawatts of electricity in 1997 and consumed 280 trillion Btu of LFG (USDoE, 1998).

In US there are 133 landfill sites that recovered LFG in 1997. Among them around 120 produce energy for generating facilities. These facilities have a combined generating capacity of 832 megawatts. They produce 5 million megawatts of electricity and consume 42 trillion Btu of LFG.

3.1.3 *Indian scenario of landfill technology*

Though India, as a tropical country, is one of the most favoured places for LFG recovery, concrete steps towards its development are lacking. A high proportion of decomposable organic material and a high moisture content in Indian MSW favour gas generation considerably (Bhide, 1994). Waste in Mumbai contains 40–60% organic components with high moisture content, whereas in the waste of New York it is around 13% (Parikh and Parikh, 1997). The lifetime of landfills in hot climatic zones is much less than that in cold climates, and that in turn means that landfills can be smaller. With all these favourable conditions, Indian MSW has the potential to produce significant energy in terms of LFG, which needs to gain economic evidence for its implementation. The US experience can be used to promote the profit-making potential of MSW and LFG under Indian conditions.

3.2 *Valuation of a landfill system with gas recovery*

The transfer of US experience to Indian conditions is not much encouraged by the fact that it has a fair chance of failure. The capacity-building process has to be carried out by learning from the US experience. A suitable scheme has to be developed and its feasibility has to be assessed before attempting its inception. Processes such as MSW management involve various external costs and benefits, which are usually ignored in conventional decision-making processes. Hence, it is essential to carry out a thorough valuation of the proposed MSW management methodology to prove that LFSGR, combined with a new scheme of waste management, would provide the most feasible solution for MSW problem. The new methodology may not be successful unless it is proved economically viable. Figure 2 shows various costs and benefits that must be considered in the valuation of MSW management. Unless all these external costs and benefits are checked, the process of landfill with gas recovery is unlikely to be successfully implemented in developing countries such as India.

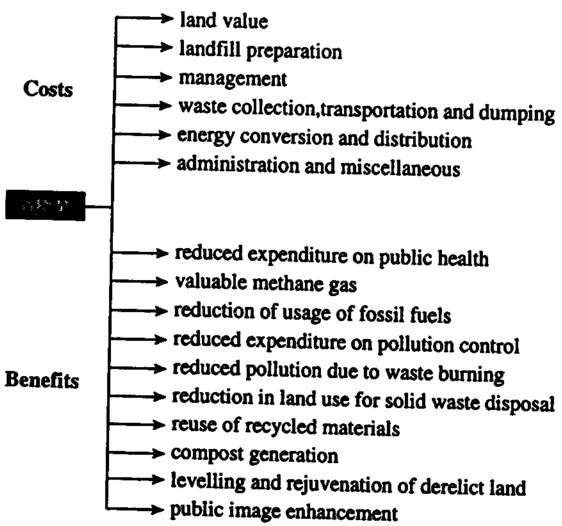


Figure 2 Various costs and benefits considered in municipal solid waste management.

The development of a landfill system with gas recovery (LFSGR) has to grow in integration with resource utilization, recycling of materials and infrastructure development for the use of the landfill gas. Because of the incentives developed by the government, the production of energy from waste grew rapidly in the US during the 1980s. Development of public policy at the federal, state and local level promoted the construction of WTE (waste to energy) facilities. Virtually all of the electricity-generating facilities that burn MSW or LFG are designated as 'qualifying facilities' (QF) by the Public Utility Regulatory Policies Act of 1978 (PURPA). Under PURPA, electric utilities are required to purchase power generated by QFs (USDoE, 1998). Structuring of such incentives encourages the development of a sustainable LFG system by minimizing the market imperfections. Figure 3 illustrates the end-use options for LFG. Success of the newly proposed methodology (shown in Appendix 1) depends highly on the development of such integrated incentive system.

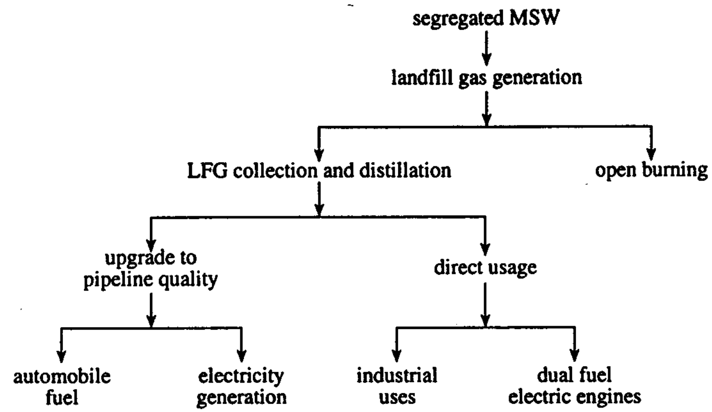


Figure 3 Energy end-use options for LFG.

The following section deals with cost–benefit analysis of the proposed system of MSW management for Mumbai, the largest metropolitan city of India.

4 Cost-benefit analysis of LFSGR: a case study

Mumbai, with a population of 10 million, is the most densely populated Indian metropolitan city, well known as the commercial capital of India. It has experienced tremendous growth in all spheres, including population, urbanization, traffic, industries, trade and solid waste generation. Future changes will only emphasize the problems of today.

The Municipal Corporation of Greater Bombay (MCGB) is responsible for the handling of solid waste, of which it collected 91% (Parikh and Parikh, 1997). Details of the Mumbai MSW in the year 1993 are presented in Table 3. The composition of this waste (Figure 4) is quite close to the Indian average values (Parikh and Parikh, 1997).

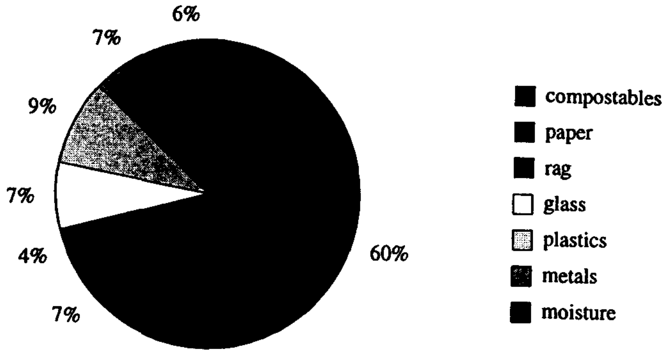


Figure 4 Composition of Mumbai municipal solid waste.

Table 3 Details of Mumbai municipal solid waste generation.

Item/characteristic	Value
Population	10 million
Total area	169 km^2
Total waste production	5000 t/day (1.825 million t/y)
Per capita generation of waste	0.5 kg
Total waste collected by MCGB	1.66 million t/yr (91% collection)
Total MCGB budget	Rs. 1230 million
Total staff of MCGB	26,239
SWM workers per 1000 population	2.5 (5 is the prescribed value)
SWM workers per tonne of waste per year	5

Mumbai's solid waste is being handled by two systems. One is a formal waste collection system and the other is informal collection by ragpickers. Mumbai houses about 100 000 ragpickers, each collecting 12 kg of waste per day, a total of 440 000 tonnes of solid waste per year. Therefore, the informal sector accounts for about 25% of the total solid waste collection.

Valuation of the existing system of waste disposal was carried out as follows, taking all external costs in to consideration.

Generation of MSW per year (W_a) = 1.825 million tonnes

Total expenditure on Mumbai MSW (MMSW) (E_t) = Rs. 1230 million

Salaries of MSW staff = Rs. 922 million (75% of E_t)

Transport = Rs. 93 million

Dumping and misc. = Rs. 215 million

The land requirement for the present-day methods of waste disposal was calculated as follows:

Average depth of landfill dump = 4 m (3–5 m range)

1 ha can accommodate 10 000 × 4 = 40 000 m^3 of waste

Density of the waste = 380 kg/m^3 [260–500 kg/m^3 range (Bhide, 1994)]

Amount of waste that can be filled in 1 ha = 40 000 × 380 kg = 15 200 t

Waste collected per day = 4550 t

Amount to be landfilled = 3412.5 t (excluding 25% of collected waste)

1 ha land will be filled in about 4.45 days (4.5 days)

Land requirement for one month = 6.66 ha ≅ 6.66 × 2.47 = 16.45 acres ≅ 17 acres

Land required per year = 204 ac (82.59 ha)

Initial value of the land = Rs. 4498.4 million (at the rate of Rs. 500/ft^2/month)

Rent that the land could command (E_1) = Rs. 1045.7 million (rent at the rate of Rs. 20/ft^2/month with a range of Rs. 9–30; 0.5 discount factor on the land)

Net Present Value (NPV) of the rent on land =

$$\frac{R_0}{1}+\frac{R_1}{(1+r)}+\frac{R_2}{(1+r)^2}+\ldots+\frac{R_{n-1}}{(1+r)^{n-1}}$$

where R is the rent at time t, r is the rate of discount, n is the life period of the landfill with $t = 0$ as the base year (John and Maynard, 1986).

Taking the life of a landfill as 10 years and a discount rate of 10%,

Net Present Value, NPV (N) = Rs. 7068.39 million

- 100 tonnes of garbage are burned every day, which results in annual emission of 3577 tonnes of SPM, 2664 tonnes SO_2, 5000 tonnes of VOC, 657 tonnes of NO_2 and 14 125 tonnes of CO.

Taking pollution abatement cost as Rs. 450 per tonnes of CO, the cost of abatement of pollution generated due to burning (E_2) is Rs. 0.63 million.

Value of reusables that comes back to the economy through ragpickers (B) = Rs. 900 million (Parikh and Parikh, 1997)

$$\text{Net expenditure for the disposal of a tonne of MSW} = Ca = \frac{E_t + [N + E_2] - B}{W_a}$$

= Rs. 4054.2 (Rs. 4055)

In general, the valuation of MSW disposal has been carried out by taking the actual costs and ignoring the externalities. The total amount spent for the disposal of 1.825 million tonnes MSW was Rs. 1230 million, or Rs. 674 per tonne. By considering the value of land, which is otherwise used for other developmental activities, pollution abatement costs and the value of reusables, the cost for one tonne of waste disposal becomes Rs. 4055. From this it is very clear that in the present scenario the cost of the waste disposal rises considerably when externalities are taken into account.

If LFSGR is implemented based on the following assumptions:

1 The waste is segregated into degradable and recyclable portions at the source itself

2 The waste bins provided are not lost

3 Institutional arrangements are made to use the landfill gas

then the following can be achieved:

- Complete return from the reusables
- Control over unhygienic conditions and the subsequent expenses
- Control over pollution caused by the burning of waste
- Reduction in the amount of land required for landfill
- The collection and transport of MSW can yield a revenue from the public (willingness to pay)
- Control over methane gas emissions and hence over expenses to mitigate GHG emissions
- Rich energy generation in terms of methane
- An alternative source of energy, which can safeguard depleting fossil fuel resources
- Control over the usage of fossil fuels and so GHG emissions, with a share from methane as fuel
- Mitigation of environmental degradation and soil and water contamination due to landfill leachate
- Production of manure for agriculture at no extra cost

Taking all these external benefits into consideration, LFSGR can be evaluated as described in the next two sections.

4.1 Costs

Annual budget allocation of MSW management by MCGB (E_t) = Rs. 1230 million

Landfill preparation costs including installation of gas collection system at highest estimation (e_h) = Rs. 35.55 million

Landfill preparation costs including installation of gas collection system at lowest estimation (e_l) = Rs. 24.885 million

(Values have been taken from USEPA handbook (USEPA, 1996) and interpolated; a factor of 0.7 was taken to eliminate the difference between prices.)

Following the scheme described in Appendix 1,

Extra cost for the collection of segregated waste at source (e_1) = Rs. 1.139 million

Area requirements

Taking an average depth of landfill as 8 metres (6–10 metres range), 1 ha can accommodate 10 000 × 8 = 80 000 m^3 of waste.

Density of the waste = 260–500 kg/m^3 (Bhide, 1994) (800 kg/m^3 after damping)

Amount of waste that can be filled in 1 ha = 80 000 × 800 kg = 64 000 t

Waste generation for one day = 5000 t

Fraction to be landfilled = 3000 t

1 ha land will be filled in 22 days

Land requirement for one month ≅ 1.36 ha ≅ 1.36 × 2.47 = 3.27 acres

Land requirement per year ≅ 16.32 ha

Present value of rent that the land could command (E_1) = 16.19 × 26.147 × 0.7 = Rs. 211.76 million

Taking the average life of the landfill as four years with one year filling and three years for gas harvest (based on an organic content of around 80%), the Net Present Value (N) is Rs. 738.385 million.

4.2 Benefits

Valuation of waste

The reusable components of municipal solid waste fetch a good price in the market, as shown in Table 4 (Parikh and Parikh, 1997).

Table 4 Value of reusable material from municipal solid waste in Mumbai.

Component	Highest value		Lowest value	
	Per day Thousand Rs.	Per year Million Rs. (b_h)	Per day Thousand Rs.	Per year Million Rs. (b_l)
Paper	350	127.75	140	51.1
Rags	80	29.20	80	29.20
Glass	35	12.77	28	10.22
Plastics	1350	492.75	675	246.37
Metal	1925	702.62	1225	447.12
Total	3740	1365.10	2148	748.01

In the case of maximum value for the reusables, the returns (Rs. 1365 million) are more than the money spent by MCGB for the entire solid waste management (Rs. 1230 million), whereas in the present scenario ragpickers return only part of the reusables to the economy.

Valuation of the landfill technology

Waste in tropical countries was found to yield 450 m^3 of landfill gas (LFG) per tonne of waste, assuming the organic fraction to be 50% (Bhide, 1994). Hence, after shredding, 720 m^3 of LFG per tonne can be expected if the organic fraction is 80%.

Total organic fraction in Mumbai MSW = 3000 t/d = 1.095 million t/y

Taking 80% as the compostable carbon = 0.876 million t/y

Total LFG production = 630 720 000 m^3

1 m^3 of methane gas = 0.722 kg

Calorific value of methane gas = 4450 kcal/m^3 = 1/0.722 × 4450 = 6180 kcal/kg

Calorific value of coal = 6692.16 kcal/kg (Coal directory, 1996)

Coal equivalent of methane gas = 6180/6692.16 = 0.92

Total methane gas in LFG (at 60% methane) = 0.6 × 630 720 000 m^3 = 273 227.904 t (multiplying by 0.722)

This is equivalent to 0.92 × 273 227.904 tonnes of coal = 251 369.671 t

Taking the cost of coal as Rs. 800 per tonne, LFG (methane dominated) gives an income of

$251\,369.671 \times 800 = \text{Rs } 201.096$ million

Value of methane as renewable energy (b_1) = Rs 201.096 million

Thus MSW in Mumbai can replace 273 227.904 tonnes of coal annually by employing an effective landfill system.

Pollution abatement costs due to waste burning are not considered because it is assumed that the entire output waste is collected, thus avoiding the need for burning.

Value of manure

Assuming 60% settlement after 4 years,

Total volume of manure from 1 ha = $10\,000 \times 8 \times 0.4 = 32\,000$ m^3

Taking the density of settled LF compost as 0.9 t/m^3, this gives a mass of 28 800 t/ha. Hence

Manure from 16.3 ha (land required for 1 year) = 469 440 t/yr

Total value of manure per annum @ Rs. 20/m^3 (b_2) = Rs. 9.388 million

By considering the above external costs and benefits along with actual costs and benefits, the unit cost of waste disposal per annum can be calculated as follows:

$$C_{LF} = \frac{E_t + e_x + e_l + N - \left[b_y + \sum_{i=1}^{2} b_i\right]}{W_a}$$

where $x = h$ or l and $y = h$ or l. Various costs and benefits that are considered in evaluating LFSGR and their values are presented in Figure 5.

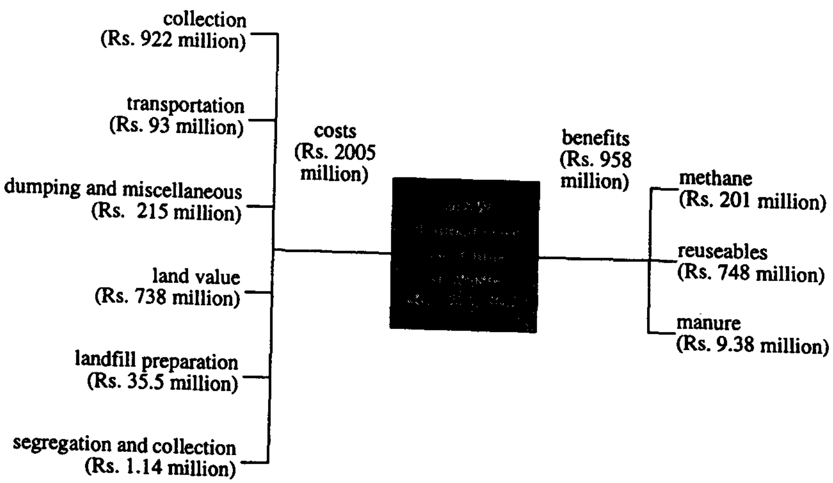


Figure 5 Representation of various costs and benefits involved in the proposed LFSGR.

The minimum cost for the disposal of one tonne of solid waste with LFSGR was found to be Rs. 222, with a maximum value of Rs. 566. When the landfill expenses are less, and also with the maximum estimated value for reusable materials, the disposal cost of MSW was found to be at its minimum. It was around a seventh of the present waste disposal cost of Rs. 4054 per tonne of MSW. With the present disposal as standard, the LFSGR could result in a saving of Rs. 3488 per tonne of MSW disposal, which is equal to Rs. 6.366 billion per annum. The difference in disposal costs of MSW in different scenarios is shown in Figure 6, and a typical valuation describing the entire MSW management valuation is given in Table 5.

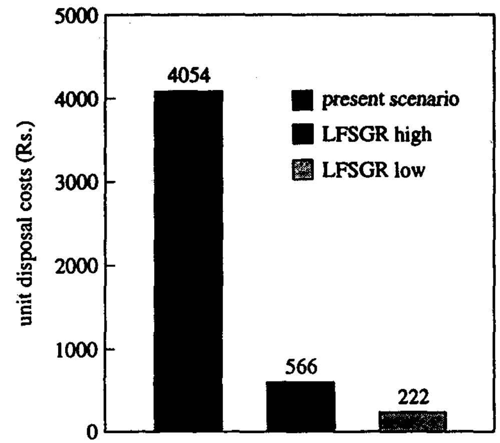


Figure 6 Comparison between different scenarios of the cost of disposal of a tonne of MSW.

Table 5 Various costs and benefits that are accounted for in the estimation of unit disposal costs.

Inputs	Outputs
Collection (accounted)	Metehan harvest (accounted)
Transportation (accounted)	Manure (accounted)
Dumping (accounted)	Reduction in land (accounted)
Cost of segragation (accounted)	Reusables (accounted)
Land value (accounted)	*Externalities:*
Landfill preparation and gas collection system (accounted)	Reduction in pollution due to waste burning (accounted)
Cost of gas utilization (unaccounted)	Reduction in GHG emission (unaccounted)
	Reduction in pollution due to methane (unaccounted)

The proposed system of waste management needs an integrated approach with active participation from people as well as the local solid waste management departments. A thorough barrier analysis has to be undertaken to determine the feasibility of adaptation. Well-structured coordination among all the concerned departments, viz. Municipalities, Department of Non-Conventional Energy Sources, Department of Urban Development, Department of Industrial Development, Department of Electricity and Pollution Control Boards is essential to overcome the barriers for this proposed new waste management methodology.

5 Conclusion

An engineered landfill system with gas recovery (LFSGR), unlike other methods of disposal, results not only in efficient solid waste management but also in renewable energy generation, and control over methane emissions to the atmosphere. In a case study of Bombay municipal solid waste, it was found that a properly managed landfill system could even yield good profits. The LFG harvest from MSW in Mumbai can replace 273 228 tonnes of coal annually and save about 80% of land that is being used for landfilling. Waste disposal expenses for a tonne of waste by LFSGR, with due consideration to the externalities, were found to be much less than those for the existing practice of waste disposal, and a huge saving of Rs. 6.366 billion per annum was calculated, with reference to the existing system of waste disposal. Barrier analysis has to be carried out to identify the frictional parameters for implementation of the proposed waste management system.

References

Bhide, A.D. (1994) 'Methane emission from landfills', *Journal IAEM*, Vol. 21, pp. 1–7.

Coal Directory (1996) *Coal after Liberalization*, CCAI, Calcutta.

Excel Environment (1999) Capability document, Excel Industries, Bombay, India.

Dixon, J.A. and Maynard, M.H. (Editors) (1986) *Economic Valuation Techniques for the Environment*, The Johns Hopkins University Press, London.

Misra, K.B. (Editor) (1993) *Clean Production: Environmental and Economic Perspectives*, Springer Publishers.

Parikh, J.K and Parikh K.S. (1997) *Accounting and Valuation of Environment, Economic and Social Commission for Asia and the Pacific*, United Nations, New York.

Proceedings of workshop on Solid Waste Management & Utilization, Dept of Chemical Engg., IIT Bombay, 7-8 November (1997).

STAPPA-ALAPCO-EPA (1999) *Methods for Estimating Greenhouse Gas Emissions from Municipal Waste Disposal*, Emission Inventory Improvement Program.

US DOE/EIA (1998) *Renewable Energy Annual 1998*, EPA publication 0603 (98)/1.

US DOE/EIA (1999) *Voluntary Reporting of Greenhouse Gas: Methane Emissions from Energy End Use*, EPA.

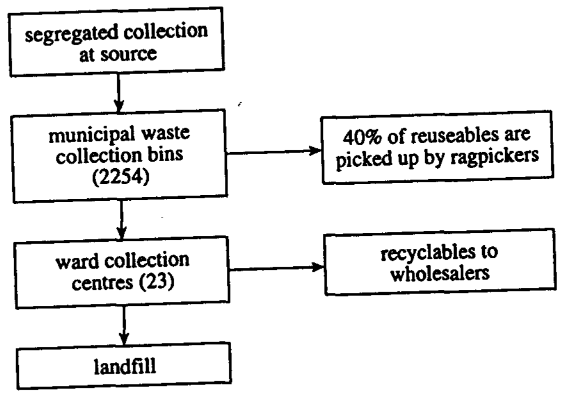
USEPA (1996) *Turning a Liability into an Asset: A Landfill Gas-to-Energy Project Development Handbook*, Landfill Methane Outreach Program, EPA.

Appendix 1 Scheme for segregated collection of waste at source

The following assumptions have been made:

- Waste generation is uniform in all 23 wards in Mumbai
- Waste is segregated at source and collected in separate bins/bags
- External costs involved in the segregation of waste at source are ignored
- As the waste is segregated, 40% of the reusable material collected by ragpickers will also get more or less equal value in the market
- The waste reaching the ward collection centre (WCC) is transported to the landfill without delay (direct shipment for disposal)
- The reusable material coming to the WCC are directed to the wholesalers directly
- The bins are placed in elevated spots to avoid water stagnation and disturbance due to stray animals

The following waste collection and disposal pathway was proposed:



Waste to be collected in the bins = 5000 t/day

With two shifts of collection system = 2500 t/day

Waste collection in each ward each time (collected twice a day) = 108 t/day

Organic fraction = 64.8 t/day

Reusable material fraction = 43.2 t/day

Assuming that a bin (municipal bin) is 1.5 m in diameter and 1 m deep,

Waste collected in each bin (organic) = 1.767 $m^3 \times 0.5$ t/m^3 = 0.8835 t

Waste collected in each bin (reusables) = 1.767 $m^3 \times 1$ t/m^3 = 1.767 t

Number of bins required for each ward (for organic) = 64.8/0.8835 = 73.34

Number of bins required for each ward (for reusables) = 43.2/1.767 = 24.45

Total number of bins for entire city (23 wards) = 23 × (74 + 25) = 2277

If each bin costs around Rs. 500, then the extra cost for the collection of segregated waste at source (e_1) is Rs. 1.139 million.