Assessment of Landfill Sustainability

G.L. Sivakumar Babu[1] P. Lakshmikanthan[2] and L.G.Santhosh[3]

[1]Professor, Dept. of Civil Engineering, Indian Institute of Science (IISc), Bangalore, Karnataka-560012. E-mail: glsivakumar@gmail.com, Phone: +91 80 2293 3124
[2]Research scholar, Centre for Sustainable Technologies, Indian Institute of Science (IISc), Bangalore, Karnataka-560012. E-mail: lakshmikanth@astra.iisc.ernet.in
Ph: +91-9036406364
[3]Research Scholar, Center for Sustainable Technologies, Indian Institute of Science (IISc), Bangalore, Karnataka -560 012, INDIA, Mob: +91-9611187003, E-mail: lgsanthu2006@gmail.com

Abstract

Assessing landfills in terms of sustainability is a difficult task and needs to be addressed comprehensively. In this paper, the social, economic and environmental sustainability of open dumps, engineered landfill and bioreactor landfill is assessed by developing suitable indicators. Factors such as global warming potential (GWP), photochemical oxidant potential (POCP), health impacts due to the emissions, cost and revenue generated from the landfills were considered as environmental, social and economic indicators which were applied for Bangalore region landfills. Eco-indicator 99 method is used to investigate the human health, ecosystem quality and resource use impact categories. The results show that the bioreactor landfill option was the preferred option for waste disposal when compared to modern landfilling as the environmental, social and economic impacts were found to be minimal in this case.

1. Introduction

Sustainability can be defined as a creation and maintenance of the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations. “Sustainable development” was defined in 1987, in the report of the World Commission on Environment and Development, as “development which meets the needs of the present without compromising the ability of future generations to meet their own needs”. According to the current understanding based on results of the Johannesburg Summit, the environment is seen as one of the three pillars of sustainable development and points out its essential interconnection with the other two pillars, namely the economic and social pillar (Fig 1). Sustainability is a complex, multidimensional phenomenon, the measurement of which requires a comprehensive set of indicators, showing the developments in its various dimensions. The assessment of sustainability is carried out through common linking indicators that indicate the social, economical and environmental effects. Indicators of sustainability are changes we can observe in the world which indicate progress toward increased sustainability.

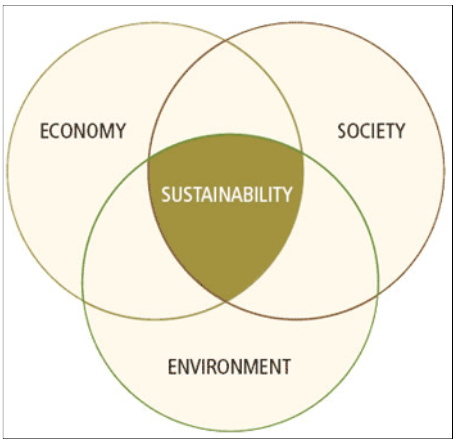

Figure 1. The three pillars of Sustainability

In this study the concept of sustainability has been applied to landfills for which the social, economic and environmental indicators are developed and analysed. Landfill has been defined by ISWA (1992) as "the engineered deposit of waste onto and into land in such a way that pollution or harm to the environment is prevented and, through restoration, land provided which may be used for another purpose". Landfills will continue to represent an important end-point of waste management. This is crucial for sustainable development as waste problems of the whole society are eventually shifted to specific areas in which they might only affect a limited number of people (contradicting intra-generative equity), and today's waste problems could be transferred to future generations because of landfills' potential long-term reactivity (contradicting inter-generative equity) (Lang et al. 2007). Therefore the assessment of the sustainability of landfills is a difficult task, which requires comprehensive site specific landfill data analysis.

2. Description of Applied Scenarios

Bangalore city, one among the eight metros in India, produces about 4500 tons per day (tpd) of municipal solid wastes (MSW). Mavallipura landfill site located in the outskirts of Bangalore has been selected for this study. It has been reported that till recently, about 60% of the MSW collected was dumped at about 60 known and unknown (unrecorded) dumping sites around Bangalore. Further, among these more than 35 sites received a mixture of domestic and industrial waste (Lakshmikantha, 2006). In this paper two cases are considered for which sustainability is assessed. The two scenarios considered for the study are given below.

Case 1: Open dumps

The open dumps are places which do not have any liner systems installed and the area is temporarily or permanently used as waste disposal sites. There is no initial costs incurred in this method but the environmental consequences are very high as the leachate may pollute the soil and ground water and the emissions could pollute the air. The boundary in this case is the area of the dump site and only the transportation charges apply. Compaction and levelling are seldom done at the site. Figure 2 shows the system boundary.

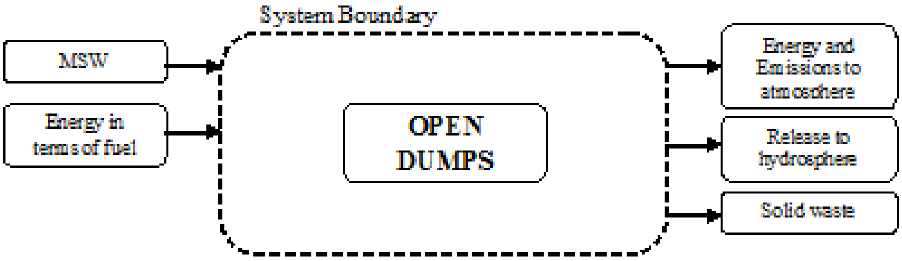

Figure 2. System Boundary of open dump

Case 2: Engineered Landfill system

This method satisfies the requirements of an engineered landfill but does not have the gas recovery system. The waste is dumped on the land which has the protective liner system and closed using the cover system. The waste undergoes anaerobic degradation and releases landfill gas (LFG) to the atmosphere. The quantity of release of LFG depends on the quantity of degradable organic content present in the waste. The LFG contains methane and carbon-di-oxide as its major constituents and traces of HCl, H_2S and HF. The CO_2 released is not accounted for in the global warming potential (GWP). Since there is no gas recovery system installed these gases are emitted into the atmosphere. Some of these gases like methane are green house gases and lead to global warming. There is also a release to the hydrosphere in the form of leachate which is controlled by the liner system and the leachate collection and treatment systems. Figure 3 shows the system boundary of the case 2.

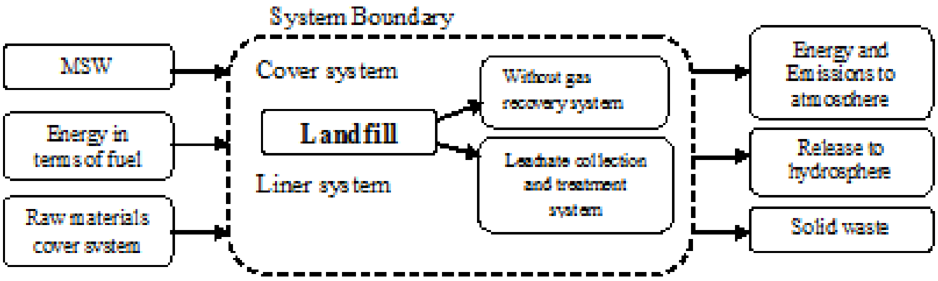

Figure 3. System Boundary of landfill without gas recovery system

Case 3: Bioreactor Landfill system

A bioreactor landfill changes the aim of land filling from the storage of waste to the treatment of waste. A bioreactor landfill is a system that enhances the degradation of refuse by microbial action. Microbial degradation may be promoted by adding certain elements (nutrients, oxygen, or moisture) and controlling other elements (such as temperature or pH). The most widely used and understood method of creating a landfill bioreactor is the recirculation of leachate, as the factor that limits microbial activity in a landfill is water. The recirculation of leachate increases the moisture content of the refuse in the landfill and, therefore, promotes waste degradation. There is a provision for leachate recirculation and landfill gas collection.

The best sustainable option in terms of minimal environmental consequences, costs and minimal social impacts is selected by comparing the impacts caused by each disposal method.

3. Methodology

Landfill sustainability is addressed through the indicators that represent the basic pillars of sustainability. Figure 4 shows the framework for assessing landfill sustainability. In order to quantify the sustainability indicators an input and output analysis of the considered scenarios has been carried out.

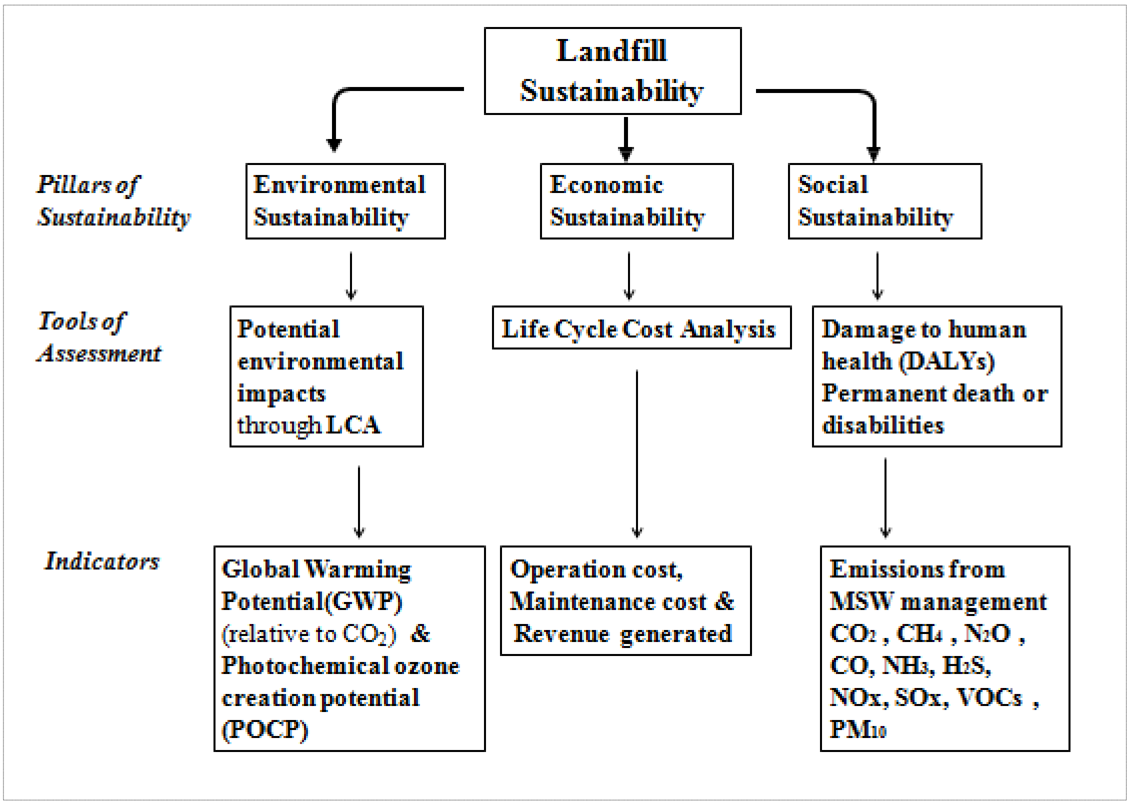

Figure 4. Framework for assessing landfill sustainability.

3.1 Input analysis

Energy inputs are those that are derived from non-renewable sources (diesel). The fuel that is required for transportation and management of waste, electricity needed for operation and maintenance, cover systems and liner systems, leachate collection and treatment system and gas collection and conversion systems are considered inputs to the system. The first scenario does not include all these things except the land. Energy consumed for the transportation of wastes to the landfill from the generation places is calculated by considering three mean distances 10, 20 and 30 kms from the disposal site. The density of the waste in the compacted trucks is considered as 425 kg/m ^{3} and each compacted truck has a capacity of 6 tonnes of MSW. Assuming an efficiency of the trucks as 3km per litre of diesel and the energy content of diesel as 36.7MJ/L the energy required for the transportation of MSW through the three mean distances is given in table 1.

Table 1. Energy required for transportation of MSW for the three considered mean distances

Distance in km	Distance (to and fro) in km	Energy required in MJ/tonne
10	20	42.8
20	40	85.6
30	60	122

Energy consumed for the management of MSW in the landfill site is calculated by assuming the capacity of the landfill as 2090000 tonnes/year (based on 2011 population and generation rate of 0.6kg/capita/day), four machines working in situ (two bull dozers and two roller compactors) and the diesel consumption of 15 Litres/hour. Assuming the working hours per day as 8h/day and 300 days/year, the energy consumed was calculated as 3 MJ/tonne of MSW. Table 2 summarises the total inputs to the disposal system.

Table 2. Inputs to the landfill system

Parameters	Values
Quantity of MSW	13.8×10^6 tonnes of MSW (for 25 years, design is done according to CPHEEO manual 2000)
Volume of daily cover	0.1% of Volume of waste (1.909×10^6 tonnes of MSW) (for 25 years, design is done according to CPHEEO manual 2000)
Volume of cover system	0.08% of Volume of waste (1.5×10^6 tonnes) (for 25 years, design is done according to CPHEEO manual 2000)
Total average rainfall in Bangalore	931 mm/year (based on 100 year data, Indian Meteorological Department)
Energy in terms of fuel	125 MJ/Tonne of MSW(3 litres of Diesel/Tonne of MSW)

3.2 Output analysis

The outputs of the landfill systems are in the form of landfill gas that is generated by the decomposition of MSW, the leachate that is being generated and finally the left over inert waste that can be used as compost. Also the emissions from the trucks and bulldozers that are used for transportation and management of MWS are considered as outputs from the system. The quantity of landfill gas that would be generated after 15 years by assuming the values given in table 3 (assuming only 40% of the total waste generated is land filled and has around 90% of degradable organic content) was calculated as 4.49×10^{12} Litres from 13.8×10^6 tonnes of MSW and 815000 Litres of biogas per tonne of MSW using the Buswell & Mueller equation. According to this relation, the methane fraction from degradation of glucose is given by

$$C_6H_{12}O_6 \rightarrow 3\ CH_4 + 3CO_2$$

This equation is considered in order to calculate the maximum emissions from the waste. It was assumed that the landfill gas contained 50% methane and 50% carbon-di-oxide. For the landfill systems with gas recovery system, there is energy savings associated with the conversion of the landfill gas (LFG) to electrical energy.

Road transport emits mainly CO_2, NO_x, CO and NMVOCs; however it is also a small source of N_2O, CH_4 and NH_3. Therefore the only major direct greenhouse gas emission is CO_2. Emissions of CO_2 are directly related to the amount of fuel used. The kilometre travelled-based CO, HC, NO_x and $PM_{2.5}$ Emission Factors of emission control technology Euro 0 Light Duty Diesel Trucks (LDDTs) are 11.95, 1.75, 2.36 and 0.62 g/km, respectively (Kebin et al 2010). The kilometre travelled-based Emission Factors of CO, HC, NO_x and $PM_{2.5}$ of Euro I Heavy

Duty Diesel Trucks (HDDTs) are 4.52±2.56, 0.68±0.19, 6.32±1.58 and 0.58±0.34 g/km. The emissions calculated based on the above mentioned values for the transportation and the management of MSW is given table 3.

Table 3. Diesel consumption for transportation and management of MSW

	Transportation				Management	
Parameters	**Emissions in g/L of diesel**	**Emissions g per tonne of MSW**			**Emissions in g/L of diesel**	**Emissions g per tonne of MSW**
Distance(to and fro) in km		20	40	60		
Diesel Consumption (Litres/tonne of MSW)		1.2	2.3	3.3		0.5
CO_2	2663[1]	3195.6	6124.9	8787.9	2663[1]	1331.5
CO	11.95	14.34	27.485	39.435	4.52	9.04
HC	1.75	2.1	4.025	5.775	0.68	1.36
NO_x	2.36	2.832	5.428	7.788	6.28	12.56
$PM_{2.5}$	0.62	0.744	1.426	2.046	0.58	1.16

1= www.ec.gc.ca

The total outputs include the methane, carbon dioxide and other gases (NO_x, $PM_{2.5}$, PM_{10} and SO_x) that are released from the landfill and are emitted by the vehicles. The landfill system with and without recovery of landfill gas are given in table 4. The efficiency of the gas collection system is assumed as 80%. The transportation distance considered here is the maximum distances of 60km. Emissions for management of waste in the open dumps are considered nil as there are no management activities undertaken.

Table 4. Total emissions from the considered landfill disposal system

Emissions from the system	**Open dumps in g**	**Engineered Landfill in g**	**Bioreactor landfill in g**
CH_4	268950	215160	53790
CO_2	289721.4	347505	78555.9
CO	48.47	48.47	48.47
HC	7.135	7.135	7.135
NO_x	22.35	20.338	20.338
$PM_{2.5}$	3.206	3.206	3.206

4. Sustainability Assessment

4.1 Environmental Sustainability

The environmental sustainability is characterised by the extent of damage done to the ecosystems. The extent of damage is assessed by some impacts and indicators. According to the life cycle characteristics of waste treatment/disposal, its environmental impacts are classified into five kinds: energy depletion potential (EDP), global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and photochemical oxidant potential (POCP). However in this paper only energy depletion potential (EDP), global warming potential (GWP) and eutrophication potential (EP) are considered. The characterisation factors of the green house gases that are considered for calculation are given in Table 5. Transportation of MSW mainly contributes to the acidification and human toxicology impacts**.**

Table 5. Characterization factors based on equivalency factors from IPCC 2001 GWP for 20 years and eco-indicator 95

IPCC 2001	
Resources	**Characterisation factors**
Global Warming Potential(GWP)	
CH4	62
CO_2	1
CO	1.57
Eco-Indicator 95	
Acidification potential (AP)	
NOx	0.7
SOx	1
NH_3	1.88
Eutrophication potential(EP)	
NOx	0.13
NH_3	0.33
Photochemical ozone creation potential (POCP)	
CH_4	0.007
Benzene	0.189
Ethene	1
Hydrocarbons,unspecified	0.398

The impacts of the respective scenarios are calculated by multiplying the equivalency factors (given in Table. 5) to the respective quantities. The equivalency factors are multiplied by the quantity of the gases released. The total impacts in disposing one tonne of waste in the two cases are given in table 6. The impacts presented in table 7 are sum of all the impacts from transportation and waste degradation.

Table 6. Indicators of the considered cases on environment for disposal of per ton of waste.

Indicators	**Open dumps in g**	**Engineered Landfill in g**	**Bioreactor landfill in g**
Global Warming Potential (GWP) **(**relative to CO_2)	16674976	13339996	3335056
Photochemical ozone creation potential (POCP)	1885.4	1508.9	379.3

Case 1 projects the maximum environmental consequences. The reason for this is the absence of the liner system, gas recovery system and the leachate collection and treatment system. The GWP and POCP are maximum in this case and therefore severely affect the environment. Therefore this is the least considered option in terms of environmental consequences. Though the impacts are less in case 2 when compared to case 1, these are only moderate. Case 3 (bioreactor landfill) emerges to be the best option. The global warming potential and Photochemical ozone creation potential (POCP) are the minimum. The advantages of bioreactor landfills described by Warith (2002) are (1) Enhancement in the LFG generation rates (2) Reduce environmental impacts (3) Production of end product that does not need landfilling (4) Overall reduction of landfilling cost (5) Reduction of leachate treatment capital and operating cost (6) Reduction in post-closure care, maintenance and risk. Hence the bioreactor landfill proves to be the environmentally sustainable option.

4.2 Economic sustainability

Life Cycle Costing (LCC) is a tool or technique that enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational and asset replacement cost. Life Cycle Cost Analysis (LCCA) is a technique used to evaluate the economic consequences over a period of time of mutually exclusive project alternatives. LCCA was applied to equipments initially. The understanding and uses of this tool have improved immensely and it is being applied to various fields, products and processes. In this study the costs considered are the direct costs (initial costs and operation and maintenance costs). The cost details given in the manual developed by the Central Public Health and Environmental Engineering Organisation (CPHEEO) have been used in this analysis. The costs are summarized in table 7.

Table 7. Cost details for a landfill

Sl.No	Item	Cost Rs x 10^5
1	**Initial Fixed Cost**	
	Site Selection and Site Characterisation Cost	26.88
	Design and Detailed Engineering Cost	17.50
	Site Development Cost	160.30
	Total	**204.68**
2	**Yearly Running Cost (Active)**	
	Phase Development Cost	427.25
	Phase Operation Cost	164.75
	Phase Closure Cost	175.95
	Total	**737.95**
3	**Yearly Running Cost (Post Closure)**	
	Post Closure Care Cost	37.00
	Total	**37.00**
	Total	**979.63**

Note: All the above mentioned prices are of base year 1998 as given in the CPHEEO manual 2000.

The above cost does not include gas recovery system. The first two scenarios do not include the gas recovery system whereas scenarios 3 and 4 include the gas recovery system. Capital costs vary according to the type of plant used to process the methane. California's capital costs varied from $606 per kW to $6,811 per kW in 2001(California Energy Commission, Landfill Gas-to-Energy Potential in California, p. 13.). It is assumed that the cost of 1 MW plant is Rs. 333x10^5.

The total gas generated is calculated by using the IPCC first order decay method. Bangalore generates 4602 ton/day of waste. Assuming the collection efficiency as 80%, waste generation as 0.6 kg/capita/day (Chanakya et al, 2009) and with present population as 9588910 (Census 2011), the methane generated over a period of 25 years is calculated as 9.5×10^6 m^3/yr. Using calorific value of methane (lowest) as 9000 kcal/m^3, energy generated in one year is computed as 358 TJ; corresponding power being 11 MW. Assuming that electricity is being sold at a price of Rs. 2 per kWh, the revenue generated due to this would be Rs. 1,98,800,000. The average life expectancy of a landfill could range from 30 to 50years. Therefore the cost analysis is done for the landfill systems for 50 years. Table 8 gives the cost and saving details of the four considered scenarios over a period of 50 years.

Table 8. Total cost details of the considered scenarios over a period of 50 years

	Case 1. Open dumps	**Case 2. Engineered Landfill**	**Case 3. Bioreactor landfill**
Initial Fixed Cost (Rs x 10^5)		204.68	204.68
Yearly Running Cost (Active) (Rs x 10^5)	-	737.95	737.95
Yearly Running Cost (Post Closure) (Rs x 10^5)	-	37	37
Gas Recovery system (Rs x 10^5)	-	-	333.33
Total		**979.63**	**1312.96**
Cost over a period of 50 years (Rs x 10^5)	-	-	1549.9 (operation and maintenance of the same site)
Total		**979.63**	**1549.9**
Total Cost over a period of 50 years (Rs x 10^5)		**1959.26**	**2862.86**
Revenue generated from electricity (Rs x 10^5)	-	-	1988
Cost savings over a period of 50 years (Rs x 10^5)			
Usage of the same Landfill site every 25 years for 50 years	-	-	204.68
Revenue generated from electricity for 50 years			3976
Total			**6168.68**
Total savings over a period of 50 years	0	**-1959.26**	**+3305.82**

Note: All the above mentioned prices are of base year 1998 as given in the CPHEEO manual 2000. The '-' sign indicates a loss and '+' sign indicates a gain/savings.

The cost details show that there is a considerable amount of saving and earnings in case 3 over a period of 50 years. The dump sites do not incur any cost except the transportation costs but may cause immense environmental consequences. Therefore it is not considered in the cost comparison with the other systems. The waste in the bioreactor is stabilized at a faster rate than the open dumps. In Case 3 the existing landfill site can be mined every 25-30 years and used again. This reduces the overall costs for case 3. The bioreactor landfill generates revenue in terms power production and also creates jobs. Hence the bioreactor landfill option is an economically viable alternative.

4.3 Social Sustainability

Social sustainability is assessed in terms of the damage that is caused on human health and is measured in terms of the disability-adjusted life year (DALY). The disability-adjusted life year is a measure of overall disease burden, expressed as the number of years lost due to ill-health, disability or early death. Traditionally, health liabilities were expressed using the expected or average number of Years of Life Lost (YLL). This measure does not take the impact of disability into account, which can be expressed by: 'Years Lived with Disability' (YLD). DALYs are calculated by taking the sum of these two components. In a formula:

$$DALY = YLL + YLD \qquad (1)$$

Carcinogenic substances cause a number of deaths each year. In the DALY health scale, death has a disability rating of 1. If a type of cancer is (on average) fatal ten years prior to the normal life expectancy, we would count 10 lost life years for each case. This means that each case has a value of 10 DALYs. During a summer smog period, many people have to be treated in hospital for a number of days. This type of treatment in a hospital has a rating of 0.392 on the DALY scale. If the hospital treatment lasts 0.01 years on average (3.65 days), each case would be weighted 0.004 DALYs. All damage factors are expressed per kg emission. The unit of damage is DALYs. The characterisation factors for the calculating the respiratory effects on humans caused by organic and inorganic substances as given by eco-indicator 99 are given in Table 9. The DALYs for both the cases is shown in Fig 5.

Table 9. Characterisation factors for calculating the respiratory effects on humans caused by organic and inorganic substances as given by eco-indicator 99

Component	Substances	Damage factor	Normalised damage factor	Weighted damage factor
Air	dust (PM_{10})	3.75E-04	2.44E-02	9.74E+00
Air	dust ($PM_{2.5}$)	7.00E-04	4.55E-02	1.82E+01
Air	NO	1.37E-04	8.90E-03	3.56E+00
Air	NO_2	8.87E-05	5.76E-03	2.30E+00
Air	NO_x	8.87E-05	5.76E-03	2.30E+00
Air	NO_x (as NO_2)	8.87E-05	5.76E-03	2.30E+00
Air	CH_4	1.19E-08	1.44E-06	7.93E-04
Air	CO_2	2.00E-07	2.42E-05	1.33E-02

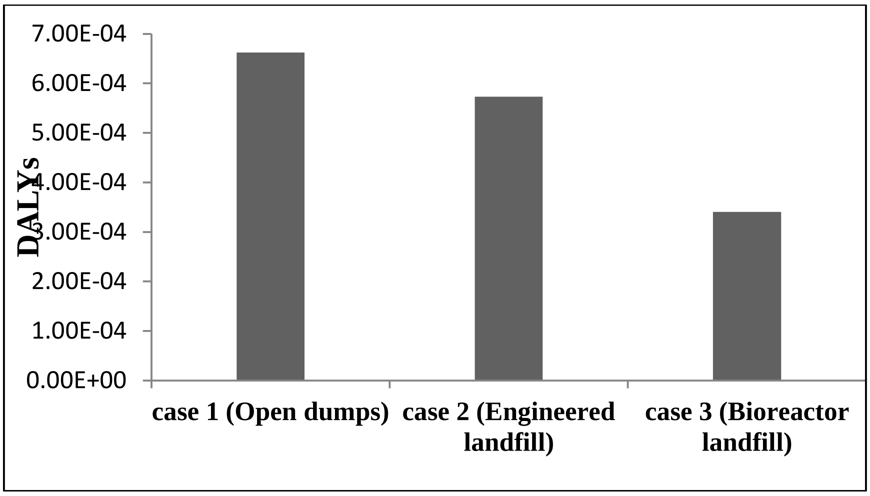

Figure 5. Summary of human health damage per ton of MSW.

Analysis of the health damage per ton of MSW processed shows that the bioreactor landfill is preferred over the open dumps due to the collection of respiratory compounds such as nitrogen oxides (NOx) and sulfur oxides (SOx) (Figure 3). On the other hand, Case 1 has the highest human health impacts. This is due to the fact that human health damages are sensitive to greenhouse gas emissions due to their climate change potential. In this scenario the main contributors to the impacts are methane, carbon dioxide and other respiratory compounds. It is evident from the Fig 5 that the maximum health damage from one ton of waste is in Case 1. The effect in case 2 is less than that in case 1 but it is the least in case 3. Therefore bioreactor landfill option is a better socially sustainable choice.

The Life cycle analysis (LCA) tool has been adopted to assess the Environmental sustainability in terms of the potential impacts to the environment. LCA serves as decision making tool in selection of the most sustainable, economic and environment friendly land disposal options. According to the life cycle characteristics of waste treatment/disposal, its environmental impacts are classified into five kinds: energy depletion potential (EDP), global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and photochemical oxidant potential (POCP). However in this study, global warming potential (GWP) and photochemical oxidant potential (POCP) are considered as these indicate the maximum negative effect on the environment.

The LCC evaluation was taken as the major economic indicator to assess the economic sustainability of the system. LCC involves evaluation of all costs in a life cycle such as capital cost, operational and maintenance cost and environmental cost.

5. Results and Discussion

The sustainability of a landfill is assessed by developing indicators representing the environmental, economical and social sustainability. Life cycle analysis, life cycle cost analysis and disability-adjusted life year are the tools employed for developing the indicators. The environmental indicators (global warming potential (GWP) and photochemical oxidant potential (POCP)) were found to be minimal in bioreactor landfill. There were jobs and revenue generated in the bioreactor landfill option. The health impacts were also minimal in bioreactor landfill compared to open dumps and engineered landfill. Bioreactor landfill has proved to be superior alternative in most of the impact categories. Therefore it can be concluded that bioreactor landfill is environmental, economical and socially sustainable means of land disposal option for waste.

6. References

Central Public Health, & Environmental Engineering Organisation (India). (2000). Manual on municipal solid waste management. Central Public Health and Environmental Engineering Orgnisation, Ministry of Urban Development, Govt. of India.

Chanakya,H.N., Shwetmala and Ramachandra, T. V. (2010): Small-scale decentralized and sustainable municipal solid waste management potential for Bangalore anchored around total recycle and biomethanation plants. National Conference on Urban, Industrial and Hospital Waste Management 2010., Ahmadabad Management Association.

Chanakya, H.N., (2009): "Towards a sustainable waste management system for Bangalore." 1st International Conference on Solid Waste Management (IconSWM), Kolkata.

Denison, R. A., (1996). Environmental life cycle comparisons of recycling , landfilling and incineration : A review of recent studies. Annual Review of Energy and the Environment, 21 : 191 - 237.

Finnveden, G., (1999). Methodological aspects of life cycle assessment of integrated solid waste management systems .Resources, Conservation and Recycling, 26, 173- 187.

IPCC, (1996). Guidelines for National Greenhouse Gas Inventories: Reference Manual. Revised.

ISO, (1997). Environmental management-life cycle assessment-principles and framework. Geneva, Switzerland: International Organisation for Standardisation.

ISWA (1992), "1000 Terms in Solid Waste Management", (Skitt, J. ed.), International Solid Wastes Association, Copenhagen, Denmark.

Kebin, H. E., Zhiliang. Yao, and Yingzhi. Zhang. (2010)."Characteristics of vehicle emissions in China based on portable emission measurement system." 19th Annual International Emission Inventory Conference "Emissions Inventories-Informing Emerging Issues", San Antonio, Texas.

Lakshmikantha, H. 2006. Report on waste dump sites around Bangalore. Waste Management. 26. 640-650.

Lang, Daniel J., et al. "Sustainability Potential Analysis (SPA) of landfills—a systemic approach: initial application towards a legal landfill assessment." *Journal of Cleaner Production* 15.17 (2007): 1654-1661.

Mendes, R. M., Aramaki, T., and Hanaki, K. (2004). Comparison of the environmental impact of incineration and landfilling in Sao Paulo City as determined by LCA, Resource. Conservation and Recycling, 41:47e63.

Warith, M. (2002). Bioreactor landfills: experimental and field results. Waste management, 22(1), 7-17.

Westlake K. Sustainable landfill-possibility or pipe-dream. Waste Management and Research 1997;15:453e61.

ANNEXURE 17.1

ESTIMATION OF LANDFILL CAPACITY, LANDFILL HEIGHT, LANDFILL AREA

1. Current Waste generation per year = W (tons per year)
2. Estimated rate of increase (or decrease) of waste generation per year = x (percent) (use rate of population growth where waste generation growth rate estimates not available)
3. Proposed life of landfill (in years) = n (years)
4. Waste generation after n years = $W \left(1 + \frac{x}{100}\right)^n$ (tons per year)

5. Total waste generation in n years (T) in tons

$$T = \frac{1}{2}\left[W + W\left(1 + \frac{x}{100}\right)^n\right] n \quad \text{(tons)}$$

6. Total volume of waste in n years (V_w) (on the assumption of 0.85 t/cm.m density of waste)

$$V_w = T/0.85 \text{ (cu.m.)}$$

7. Total volume of daily cover in n years (V_{dc}) (on the basis of 15 cm soil cover on top and sides for lift height of 1.5 to 2 m)

$$V_{dc} = 0.1\, V_w \text{ (cu.m.)}$$

8. Total volume required for components of liner system and of cover system (on the assumption of 1.5m thick liner system (including leachate collection layer) and 1.0 m thick cover system (including gas collection layer)

$$V_c = k\, V_w \quad \text{(cu.m.)}$$

(k = 0.25 for 10 m high landfill, 0.125 for 20 m high landfill and 0.08 for 30 m high landfill. This is valid for landfills where width of landfill is significantly larger than the height)

9. Volume likely to become available within 10 years due to settlement / biodegradation of waste

$$V_s = m V_w$$

(m = 0.10 for biodegradable waste; m will for less than 0.05 for incinerated/inert waste)

10. First estimate of landfill capacity (C_i)

$$C_i = V_w + V_d + V_c - V_s \quad \text{(cu.m.)}$$

11. Likely shape of landfill in plan and section (To be based on topography of area, depth to ground water table and other factors) :
Area type, trench type, slope type, valley type, combination

12. First estimate of landfill height and area

(a) Restricted area available = A_r (sq.m.)
Area required for infrastructural facilities = 0.15 A_r
Area available for landfilling = 0.85 A_r
Average landfill height required (first estimate) above base level
$H_i = C_i / 0.9 A_r$ (m) (valid for area type landfill)

(b) No limitation on Area
Possible maximum average landfill height (first estimate) = H_i (typically between 10 to 20 m, rarely above 30 m)
Area required for landfilling seperations

$$A_i = C_I / H_i \quad \text{(sq.m.) (valid for area type landfill)}$$

Total area required (including infrastructural facilities) (first estimate)

$$A_i = 1.15 A_i$$

13. Refinement in estimates of landfill capacities, landfill height and landfill area:

After obtaining the initial estimates, the volume of daily cover as well as volume of liner system and cover system can be revised keeping in view the shape of the landfill as well as on the basis of whether materials of daily cover, liner system and cover system will be excavated from within the landfill site.

Taking these revised values into account, refined estimates of landfill capacity, height and area can be made. The final and precise estimates will be arrived at after topographical survey results (0.30 m contour interval) become available.

It may be noted that landfill capacity values will undergo revision during operation of the landfill when waste quantities delivered at the site vary from the generation rates estimated prior to the start of landfill operations.

ANNEXURE 17.2

TYPICAL EXAMPLE (PRELIMINARY DESIGN)

The example given below is applicable for preliminary design of a landfill. Detailed design is not covered in this example. The word ‘tentative’ is used wherever adequate information was not available and when an adhoc estimate has been made.

17.A2.1 BASIC DATA

Location	:	Delhi
Waste Generation	:	1000 tons per day (current)
Design Life	:	Active Period = 16 years
		Closure and Post Closure Period=25 years
Topography	:	Flat ground
Subsoil	:	Sandy SILT upto 20m below ground surface, underlain by bedrock
Water-table	:	10m below ground surface
Average Total Precipitation	:	750 mm per year
Base year	:	1998 prices

17.A2.2 LANDFILL CAPACITY, LANDFILL HEIGHT, LANDFILL AREA

(a) Current Waste Generation Per Year = 1000 t

(b) Estimated Waste Generation After 16 Years = 1700 t

(c) Total Waste Generation in 16 Years

$= 0.5 (1000 + 1700) \times 365 \times 16$

$= 7 \times 10^6$ tons

(d) Total Waste Volume (assumed density 0.85 t/cu.m.)

= $(7 \times 10^6)/0.85$
= 8.25×10^6 cu.m.

(e) Volume of Daily Cover

= $0.1 \times 8.25 \times 10^6$
= 0.825×10^6 cu.m.

(f) Volume of Liner and Cover Systems

= $0.125 \times 8.25 \times 10^6$
= 1.03×10^6 cu.m.

= 0.825×10^6 cu.m.

(g) First Estimate of Landfill Volume

Ci = $(8.25 + 0.825 + 1.03 - 0.825) \times 10^6$

= 9.28×10^6 cu.m.

(h) Likely Shape of Landfill

Rectangular in plan (length : width = 2:1)

Primarily above ground level, partly below ground level.

(i) Area Restrictions : Nil

(j) Possible Maximum Landfill Height = 20 m

(l) Area Required = $(9.28 \times 10^6)/20$

= 4.15×10^5 sq.m.

(m) Approximate Plan Dimensions = 450 m x 900 m

(n) Actual Landfill Section And Plan : Discussed in Section 17.A2.3.

17.A2.3 LANDFILL SECTION AND PLAN

(a) Landfill Section and Plan is evaluated on the basis of

(i) 4:1 side slope for the above-ground portion of the landfill.
(ii) 2:1 side slope for the below-ground portion of the landfill.
(iii) Material balance for daily cover, liner and final cover material through excavation at site.
(iv) Extra space around the waste filling area for infrastructural facilities.

(b) The final plan and section adopted is shown in Fig. 17.A2.1.
(c) Additional 30m land is acquired around the landfill to place infrastructure facilities. Final size of landfill = 572 m x 1172 m.

17.A2.4 LANDFILL PHASES

(a) Active life of landfill = 16 years
(b) Duration of one phase = one year
(c) Number of phases = 16. Each phase extends from base to final cover.
(d) Volume of one phase == landfill capacity/16
(e) Plan area of phase
= (Volume of one phase)/landfill height
= 240 m x 120 m (approx.)
(f) Number of daily cells = 365
(g) Plan area of one cell /on the basis of 2.0m lift of each cell
= (Volume of one cell)/2.0
= 22 x 42 m (approx.)
Landfill phases are shown in Fig. 17.A2.2.

17.A2.5 LANDFILL INFRASTRUCTURE & LAYOUT

(a) Site Fencing: All around the landfill

(b) Weighbridges: Two weighbridges of 50T capacity
(computerised) (entry and exit) with office

(c) Administrative office: 30 m x 10 m building

(d) Site control office: 3m x 5m (portable cabin)

(e) Access Roads:

(i) Main Access Road : 7m wide; from main road to parking area after weigh- bridge.

(ii) Arterial Road: 3.5 m wide all along the periphery.

(f) Waste Inspection And Sampling Facility: Nil; to be done at landfill area.

(g) Equipment Workshop & Garage: 30m x 20m building

(h) Vehicle Cleaning: Within the Workshop

(i) Other Facilities

(a) Temporary Holding Area: Excavated portion of half phase to be used
(b) Surface water drain: Adjacent to arterial road along periphery
(c) Leachate collection pipe: Adjacent to arterial road along periphery
(d) Leachate holding tank: 20x10x3m
(e) Leachate treatment facility: 40mx20m (in plan) (tentative)
(f) Gas Flaring facility: 20m x 10m (in plan) (tentative)
(g) Surface water sedimentation tank : 40 x 10 x 1.5m

All infrastructural facilities are shown in Fig. 17.A2.3.

17.A2.6 LINER AND LEACHATE COLLECTION SYSTEM

(a) Liner System

The liner system will comprise of the following layers below the waste:

(i) 0.30 m thick drainage layer comprising of Badarpur sand (coarse sand) or gravel (stone dust with no fines)
(ii) 0.2m thick protective layer of sandy silt (Delhi silt)
(iii) 1.50mm thick HDPE geomembrane
(iv) 1.0 m thick clay layer/amended soil layer (since clay is not easily available in Delhi, amended soil layer comprising of local soil + bentonite is to be designed)

(b) Amended Soil Layer Design Through Laboratory Testing

Sandy silt mixed with bentonite in proportions of 2, 4, 6, 8 and 10% in laboratory and permeability determined. Minimum bentonite content determined for achieving permeability of less than 10^{-9}m/sec. 5% Bentonite + sandy silt assumed in preliminary design.

(c) Leachate Evaluation

Average Total Precipitation in Delhi = 750mm/year
Only one phase is operative every year
Plan area of operating phase = 29000 sq.m.
Assuming 80% precipitation in 4 months (monsoooon period), peak leachate quantity (thumbrule basis) = 200 cu.m. per day

(d) Leachate Collection Pipes

Dia of HDPE pipes (perforated) = 15 cm
Spacing of pipe required (hydraulic analysis) = 22m

(e) Leachate Holding Tank

Size of holding 3 days of leachate = 20 x 10 x 3 m

Liner system and leachate collection pipes shown in Figs. 17.A2.4 and 5.

17.A2.7 COVER SYSTEM DESIGN

(a) Cover System

The cover system will comprise of the following layer above the waste.

(i) 0.45 m thick gas collection layer comprising of gravel (stone dust with no fines)
(ii) 0.6 m thick barrier layer (sandy silt + 5% bentonite)
(iii) 0.3m thick surface layer of local top soil for vegetative growth

(b) Passive Gas Vents

Passive gas vents 1m high (above ground surface) will be provided at a spacing of 75mx75m.

17.A2.8 SURFACE WATER DRAINAGE SYSTEM

(a) Surface Water Runoff

Average Total Precipitation in Delhi = 750 mm/year

Peak discharge rate reaching drainage channel = 0.064 cu.m./sec.

Dimensions of drainage channel:
Depth = 0.6m, Base width = 0.6m, side slopes = 3:1

(b) Sedimentation Tank

To remove suspended particles of size 40 microns and above tank size required
= 40 x 15 x 1.5

Surface water drainage system depicted in Fig. 17.A2.6.

17.A2.9 ENVIRONMENTAL MONITORING SYSTEM

(a) Ground Water Monitoring Wells

Numbers = 6 (1 upgradient well; 5 wells along the sides in downgradient direction; all wells 30m away from landfill)

(b) Lysimeters

Numbers = 2 lysimeter under each phase. Total nos. = 32.

(c) Gas Monitors

Two portable gas monitors for landfill gas.

(d) Samplers

Stainless steel/HDPE samplers (25 nos.) for
(i) Groundwater samples
(ii) Leachate samples in vertical risers/wells

Grab samplers for landfill gas (25 nos.) at

(i) Passive vents
(ii) Gas wells

(e) Downhole Monitors

One multiparameter downhole groundwater monitoring system.

ANNEXURE 17.3

ESTIMATION OF LANDFILL COST BASED ON PRELIMINARY DESIGN

TABLE 1: SITE SELECTION AND SITE CHARACTERISATION COST

Sl. No.	**Item**	**Cost Rs x 10^5**
1.	Data Collection	0.50-0.75
2.	Environmental Impact Assessment	4.00-6.00
3.	Preliminary Bore Holes	1.50-2.25
4.	Geotechnical Investigation for Design , Borrow Material , Ground Water Investigation	7.50-11.25
5.	Topographical Investigation	1.50-2.25
6.	Hydrological Investigation	2.00-3.00
7.	Geological Investigation	2.00-3.00
8.	Traffic Investigation	0.50-0.75
9.	Water and Leachate Investigation	2.00-3.00
	Total	21.50-32.25
	Average	26.88

Note: This estimate is lumpsum and approximate. The values are indicative. However, actual costs will vary from site to site and should not be restricted by the range indicated in the table.

TABLE 2: DESIGN AND DETAILED ENGINEERING COST

Sl. No.	**Item**	**Cost Rs x 10^5**
1.	Design and Detailed Engineering	15.00-20.00
	Average	17.50

Note: This estimate is lumpsum and approximate. The values are indicative. However, actual costs will vary from site to site and should not be restricted by the range indicated in the table

TABLE 3: SITE DEVELOPMENT COST

Sl. No.	Item	Cost Rs x 10^5	Cost Rs x 10^5
1.	Land Acquisition*	830.00	
2.	Cost of Infrastructure		102.70
3.	Equipment for Landfill Construction/Operation **	359.00	
4.	Surface Water Drainage System		30.75
5.	Leachate Management Facility		23.85
6.	Environmental Monitoring Facility		8.00
7.	Gas Collection Facility***		
	Total	1189.00	160.30

** Land acquisition cost will vary drastically from location to location; market value indicated but not included in costing.*
*** Equipment cost indicated but not included in costing since all earthwork / waste placement work are computed on job basis.*
**** Not included in the example but to be taken into account whenever gas is collected for energy recovery / flaring.*

TABLE 4: PHASE DEVELOPMENT COST (YEARLY)

Sl. No.	Item	Cost Rs x 10^5
1.	Up-dated Design of Phase	2.00
2.	Preliminary Operation	112.10
3.	Temporary Surface Water Drains	0.80
4.	Monitoring Facility Below Liner	2.00
5.	Liner System	261.85
6.	Leachate Collection and Removal System	8.45
7.	Maintenance of Existing Facility	40.05
	Total	427.25

TABLE 5: PHASE OPERATION COST (YEARLY)

Sl. No.	Item	Cost Rs x 10^5
1.	Waste Filling , Spreading and Compaction	171.30
2.	Daily Cover Laying , Spreading and Compaction	19.45
3.	Pollution Prevention During Operation	4.00
	Total	164.75

TABLE 6: PHASE CLOSURE COST (YEARLY)

Sl. No.	Item	Cost Rs x 10^5
1.	Final Cover System	130.25
2.	Surface Water Drainage System on Cover	10.30
3.	Monitoring Facility on Cover	1.00
4.	Vegetation Growth on Cover	4.40
	Total	175.95

TABLE 7: POST CLOSURE CARE COST (YEARLY)

Sl. No.	Item	Cost Rs x 10^5
1.	Long Term Vegetative Stabilisation	16.00
2.	Operation of Leachate Management Facility	5.00
3.	Maintenance of Cover and Drainage System	12.50
4.	Environmental Monitoring	3.50
	Total	37.00

TABLE 8: INITIAL FIXED COST

Sl. No.	Item	Cost Rs x 10^5
1.	Site Selection and Site Characterisation Cost (Table 1) Average	21.50-32.25 26.88
2.	Design and Detailed Engineering Cost (Table 2) Average	15.00-20.00 17.50
3.	Site Development Cost (Table 3)	160.30
	Total	204.68

TABLE 9: YEARLY RUNNING COST (ACTIVE)

Sl. No.	Item	Cost Rs x 10^5
1.	Phase Development Cost (Table 4)	427.25
2.	Phase Operation Cost (Table 5)	164.75
3.	Phase Closure Cost (Table 6)	175.95
	Total	737.95

TABLE 10: YEARLY RUNNING COST (POST CLOSURE)

Sl. No.	Item	Cost Rsx10^5
1.	Post Closure Care Cost (Table 7)	37.00
	Total	37.00