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# Optimization model for integrated municipal solid waste management in Mumbai, India

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ABSTRACT. Mumbai, the largest metropolitan city in India, generated 6,256 tons of waste per day in 2001. It is the responsibility of the Municipal Corporation of Greater Mumbai (MCGM) to provide Municipal Solid Waste (MSW) management services; however, the MCGM is not able to handle the increasing quantity of waste. As a result, waste litters all over the place giving rise to health and environmental problems. Hence, there is a need to involve private sector and community participation in waste management. In this paper, a linear programming model is developed to integrate different options and stakeholders involved in MSW management in Mumbai. Various economic and environmental costs associated with MSW management are taken into consideration while developing the model.

## Introduction

Waste is an unavoidable by-product of human activities. Economic development, urbanization and improved living standards in cities increase the quantity and complexity of generated solid waste. If accumulated, it leads to degradation of urban environment, stresses natural resources and leads to health problems (CPCB, 2000; NEERI, 1994; UN, 2000). Cities in the world are facing a high level of pollution; the situation in developing countries is more acute, this is partly caused by inadequate provision of basic services like water supply, sanitation facilities, transport infrastructure and waste collection (UNCHS Habitat, 2001). Municipal corporations of the developing countries are not able to handle the increasing quantity of waste, which leads to uncollected waste on roads and other public places.

Mumbai, the largest metropolitan city in India, presents one of the most critical Solid Waste Management (SWM) systems. The population of Mumbai grew from 9.9 million in 1991 to 11.9 million in 2001, an increase of 20 per cent (Director of Census Operations, 2001). During the same period Municipal Solid Waste (MSW) increased from 4439 to 6256 tons per day, an increase of 41 per cent, (NEERI, 1994; MCGM, 2001). This implies that the per capita waste generation has increased from 0.45 kg to

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Table 1. *MCGM budget and expenditure on SWM*

| *Year* | *MCGM budget per year in million Rs. (million $*)* | *Money spent on SWM services per year in million Rs. (million $)* | *Waste generated (Tons)* | *Money spent per ton in Rs. ($)* |
|---|---|---|---|---|
| 2000–01 | 52,456 (1206) | 3,500 (81) | 6,256 | 1,533 (35) |
| 2001–02 | 61,435 (1413) | 3,982 (92) | 6,500 | 1,678 (39) |

* 1 US dollar = Rs. 43.5 Reserve Bank of India www.rbi.org.in, date of access July 15th 2005.
*Source*: MCGM (2001–2002).

0.53 kg per day over the above mentioned period. This clearly indicates that the growth rate of MSW in Mumbai has outpaced population growth rate. Table 1 gives an account of the budget of the Municipal Corporation of Greater Mumbai (MCGM) and money spent on providing SWM services. In spite of spending a large amount of money on SWM services, the MCGM has failed to keep the city clean.

There is an emerging global consensus to develop local level solutions and community participation for better MSW management (UN, 1992). NIUA (1999), Memon (2002) and UNESCAP (2002) explain successful case studies of community participation in waste management in different cities. A study conducted by Beukering *et al.* (1999) emphasizes citizens' awareness and involvement for better waste management. Some of the places encouraging private sector participation for delivery of waste services are Sao Paulo, Brazil, Malaysia and Nepal (Bartone *et al.*, 1991; Manandhar, 2002).

A number of studies were carried out in the past to compare different methods of waste disposal and processing for different places. Maimone (1985) conducted a study for the Netherlands and concluded that composting was the best option of waste management. In another study done for the United Kingdom refused derived fuel was found to be the best option (Powell, 1996). There are a number of studies, namely Chung and Poon (1996), Poerbo (1991), Beukering (1997), suggesting different methods of waste management for different places.

It can be inferred from the literature that no one method in isolation can solve the problem of waste management. There is a need to combine different methods and stakeholders in such a way so as to minimize environmental and social costs associated with waste management. Gerlagh *et al.* (1999) have developed a linear programming model to integrate different methods of waste management in Bangalore, India. The present study is an attempt to integrate the best feasible method of waste management in Mumbai considering various economic and environmental costs. In this paper, an optimization model has been developed to integrate the following options of waste management in Mumbai:

1. **Community compost plant:** Community participation in waste management has been initiated in Mumbai as a result of good urban governance campaign, which started as a joint project between the

Government of India and the MCGM in collaboration with United Nations Centre for Human Settlements. This model of decentralized waste management system is called 'Advanced Locality Management (ALM)'. ALM is a community based approach for effective management of civic services at the grass root level. It is based on the principle of cooperation and partnership amongst Community Based Organizations (CBOs), Non-Governmental Organizations (NGOs) and the MCGM for managing civic services at the local level.

The ALM model works as follows: the locality participating under this scheme forms a committee, which is responsible for planning, implementing and inspecting various aspects of locality development. It also coordinates between the MCGM and local residents for smooth functioning of civic services. The MCGM appoints an officer at the ward[1] level to look into citizens' complaints and coordinate with the local committee. All residents who fall under the ALM scheme have to segregate their waste into biodegradable and recyclable material. Rag pickers organised and trained by NGOs collect these wastes and sort them out further. They process biodegradable waste and sell the recyclable material. The MCGM provides subsidy and technical help to construct composting pits in these areas and it also gives priority attention to such areas for other civic services. In this scheme NGOs play a very important role by organising rag pickers and giving them necessary training for collecting and composting waste.

2. **Mechanical aerobic compost plant:** Excel Industry Limited was established in 1941 and is one of India's larger agro chemical companies. It converts the organic component of MSW in Mumbai into manure through mechanical aerobic composting. It processes 30 to 40 tons of waste per day. Waste is supplied for free from the MCGM to Excel Industry. Under this partnership waste is collected and transported by the MCGM and Excel Industry processes waste by aerobic composting. All inert material separated by the company is transported back to dump sites by the MCGM.
3. **Sanitary landfill:** The functions of the MCGM have been delineated in various provisions of the BrihanMumbai Municipal Corporation (B.M.C.) Act 1888. One of the functions of the MCGM is to provide SWM services in Mumbai. The MCGM collects, transports and disposes of municipal solid waste generated in Mumbai. The MCGM currently uses the sanitary landfill method to dispose of collected waste.

## Model

This section describes the mathematical formulation of the linear programming model for integrated waste management planning. Objective functions and model constraints are derived taking into consideration both economic and environmental costs.

[1] Wards are subdivisions of Mumbai city into smaller parts for administrative purposes.

Let's assume

| | |
|---|---|
| Generation node | $i$ |
| Mechanical aerobic composting | $a$ |
| Community compost plant | $v$ |
| Sanitary landfills | $o$ |

| **Decision variables** | **waste transported from** | **to** |
|---|---|---|
| $W_{ia}$ | generation node $i$ | Aerobic compost plant '$a$' |
| $W_{iv}$ | generation node $i$ | Compost plant '$v$' |
| $W_{io}$ | generation node $i$ | sanitary landfill '$o$' |
| $W_{ao}$ | Aerobic compost plant '$a$' | sanitary landfill '$o$' |
| $W_{vo}$ | Compost plant '$v$' | sanitary landfill '$o$' |

**Objective function**

The objective function includes minimization of net cost of integrated solid waste management (ISWM) system

$$Minimize(CT - BT)$$

where

$CT$ is total cost associated with ISWM stream
$BT$ is total benefit associated with ISWM stream

*Cost*

$$\sum_a CA_a = \sum_a\sum_i coll * W_{ia} + \sum_a\sum_i t * D_{ia} * W_{ia} + \sum_a\sum_i oca * W_{ia} + \sum_a\sum_i lca * W_{ia} + \sum_a\sum_i envca * W_{ia} * bio + \sum_a\sum_o ocod * W_{ao} + \sum_a\sum_o lcod * W_{ao} + \sum_a\sum_o envcod * W_{ao}$$

$$\sum_v CV_v = \sum_v\sum_o coll * W_{vo} + \sum_v\sum_i ocv * W_{iv} * bio + \sum_v\sum_i lcv * W_{iv} + \sum_v\sum_i envcv * W_{iv} * bio + \sum_v\sum_o ocod * W_{vo} + \sum_v\sum_o t * D_{vo} * W_{vo} + \sum_v\sum_o lcod * W_{vo} + \sum_v\sum_o envcod * W_{vo}$$

$$\sum_o COD_o = \sum_i\sum_o coll * W_{io} + \sum_o\sum_i t * D_{io} * W_{io} + \sum_o\sum_i ocod * W_{io} + \sum_o\sum_i lcod * W_{io} + \sum_o\sum_i envcod * W_{io}$$

$$CT = \sum_a CA_a + \sum_v CV_v + \sum_o COD_o$$

where

$CA_a$ = total cost of waste processing at aerobic composting plant '$a$'
$CV_v$ = total cost of waste processing at community compost plant '$v$'
$COD_o$ = total cost of waste disposal at sanitary landfill $o$
$t$ = transportation cost per ton of waste per km
$D_{ia}$ = distance from generation node '$i$' to aerobic composting plant '$a$'
$D_{vo}$ = distance from compost plant '$v$' to sanitary landfill '$o$'
$D_{io}$ = distance from generation node '$i$' to sanitary landfill '$o$'
$bio$ = fraction of biodegradable material in total waste
$oca$ = operating cost per ton of waste for aerobic composting plant
$ocv$ = operating cost per ton of waste for community compost plant
$ocod$ = operating cost per ton of waste for sanitary landfill
$lcv$ = land cost associated with community composting
$lca$ = land cost associated with aerobic composting
$lcod$ = land cost associated with sanitary landfill
$envca$ = environmental cost per ton of waste for aerobic composting
$envcv$ = environmental cost per ton of waste for community compost plant
$envcod$ = environmental cost per ton of waste for sanitary landfill

*Benefits*
Benefits are derived from recyclable material and compost produced from community compost plants and aerobic compost plants.

$$\sum_a BA_a = \sum_a \sum_i fca * pca * W_{ia} * bio + \sum_a \sum_i \sum_r fr_r * pr_r * W_{ia}$$

$$\sum_v BV_v = \sum_v \sum_i fcv * pcv * W_{iv} * bio + \sum_v \sum_i \sum_r fr_r * pr_r * W_{iv}$$

$$\sum_o BCOD_o = \sum_o \sum_i \sum_r fr_r * pr_r * W_{io}$$

$$BT = \sum_a BA_a + \sum_v BV_v + \sum_o BCOD_o$$

where

$BA_a$ = total benefits of waste processing at aerobic composting plant '$a$'
$BV_v$ = total benefits of waste processing at community compost plant '$v$'
$BCOD_o$ = total benefits of waste management under sanitary landfill
$BT$ = total benefits of waste management
$fr_r$ = fraction of recyclable material '$r$' in total waste
$pca$ = price of aerobic compost
$pcv$ = price of community compost
$fca$ = compaction factor for aerobic compost plant
$fcv$ = compaction factor for community compost plant
$pr_r$ = price of recyclable material '$r$'

*Constraints*
Mass balance constraints
All solid waste generated at a source *i*, should be transported either to a community compost plant *v* or to an aerobic compost plant *a*, or to a sanitary landfill *o*.

$$\sum_{v} W_{iv} + \sum_{a} W_{ia} + \sum_{o} W_{io} = G_i$$

where

$G_i$ = amount of waste generated at generation node '*i*'

Capacity limitation constraints
Planned capacity at each facility should be less than or equal to the maximum allowable capacity of the facility.

$$\sum_{i} W_{ia} \leq Cap_{max,a}$$

$$\sum_{i} W_{iv} \leq Cap_{max,v}$$

where

$Cap_{max,\,a}$ = maximum capacity of aerobic compost plant '*a*'
$Cap_{max,\,v}$ = maximum capacity of community compost plant '*v*'

Material limitation constraints
It implies that all inert material reaching community compost plants and aerobic compost plants has to be transported to sanitary landfill.

$$\sum_{o}\sum_{v} W_{vo} \geq \sum_{i}\sum_{v} fin * W_{iv}$$

$$\sum_{o}\sum_{a} W_{ao} \geq \sum_{i}\sum_{a} fin * W_{ia}$$

where

*fin* = fraction of inert material in total waste
$W_{vo}$ = amount of waste transported from community compost plant to open dump
$W_{ia}$ = amount of waste transported from aerobic compost plant to sanitary landfill

**Model application**
This optimization model has been applied to the waste management system for the whole of Mumbai. Every ward is considered as a generation node and it is assumed that every generation node has a community compost plant. There are 24 wards and hence 24 generation nodes. The amount of waste generated from different wards and the distance of generation node from

Table 2. *Waste generated from ward i ($W_i$) and distance from generation node to dumpsite*

| | | Distance in km | | |
|---|---|---|---|---|
| *Wards* | $W_i$ *(ton)* | *Deonar* | *Mulund* | *Gorai* |
| A | 223.67 | 24 | 32 | 45 |
| B | 134.38 | 19.75 | 27.25 | 40 |
| C | 203.3 | 23 | 31 | 44 |
| D | 352.46 | 21.5 | 29.5 | 43 |
| E | 299.66 | 19 | 27 | 40 |
| F/S | 283.58 | 14.5 | 22.5 | 35 |
| F/N | 204.93 | 11.5 | 19.5 | 33 |
| G/S | 209.5 | 16.5 | 24.5 | 34 |
| G/N | 382.63 | 14.25 | 22.25 | 35 |
| H/E | 150.65 | 13.75 | 22.25 | 35 |
| H/W | 233.66 | 14.25 | 24 | 37 |
| K/E | 331.93 | 21 | 19 | 17.5 |
| K/W | 312.88 | 20.5 | 19 | 17.5 |
| P/S | 229.98 | 22 | 19 | 11.5 |
| P/N | 271.22 | 24 | 21 | 8.5 |
| R/S | 152.44 | 33 | 27 | 5.9 |
| R/C | 198.24 | 35 | 29 | 3.6 |
| R/N | 165.94 | 36 | 30 | 5 |
| L | 250.98 | 11 | 19 | 33.5 |
| M/E | 352.69 | 5.5 | 17 | 39 |
| M/W | 465.19 | 2 | 14 | 41 |
| N | 178 | 7.75 | 13 | 30 |
| S | 221.05 | 13 | 8.75 | 26 |
| T | 165.17 | 18 | 4.5 | 22 |

*Notes*: Table gives distance from ward check post to nearest dumping ground check post. It further gives distance to the next closest dumping ground check post. Rest of the distances is calculated from the Mumbai city map considering crow fly distance from centre of ward to the dumping ground.
*Source*: MCGM (2001).

dumpsites is provided in table 2. Three disposal sites have been considered in the model. It is assumed that aerobic composting plants are situated near every disposal site so that cost of transportation of inert material is negligible. There are 801 decision variables and 53 constraints in this model.

| | |
|---|---|
| Generation node ($i$) | = 24 (municipal wards) |
| Aerobic composting plant ($a$) | = 3 (one near every dump site) |
| Compost plant ($v$) | = 24 (one in every ward) |
| Sanitary landfills ($o$) | = 3 |
| Number of decision variables | = (i*a + i*v + i*o + a*o + v*o) |
| | (24*3 + 24*24 +24*3 +3*3 +24*3) |
| | = 801 |
| Number of constraints | = I + v + a + 2 |
| | = 53 |

Table 3. *Estimation of environmental cost associated with different options of waste management*

| *Material* | *Environmental cost (average figures) ($ per ton)*[a] | *Composition of Mumbai MSW*[b] *(per cent)* | *Environmental cost for waste generated in Mumbai ($ per ton)* |
|---|---|---|---|
| | | Landfill | |
| Paper | 24.96 | 7.9 | 1.97 |
| Plastics | 43.84 | 4.86 | 2.13 |
| Glass | 11.27 | 1.88 | 0.21 |
| Metals | 53.06 | 0.97 | 0.51 |
| Organics | 23.66 | 38.98 | 9.22 |
| Other waste | 9.13 | 45.26 | 4.13 |
| Total | | | 18.18 |
| | | Composting | |
| Organics | 18.29 | 38.98 | 7.12 |

[a]: CIWMB (1991), page no. 6–54.
[b]: NEERI (1994).

**Data requirement**

Data on MSW management in India are not readily available and Mumbai is no exception to this. Hence, questionnaires were prepared and personal interviews were carried out with concerned resource personnel in the MCGM, Stree Mukti Sangathan (SMS), an NGO actively involved in MSW management in Mumbai and Excel Industry, a private sector involved in waste management, to get the necessary information and data for the present study. Some of the other organizations which provided necessary data for the present study are Bhawalkar Ecological Research Institute, Exnora and Pakruti. Data were collected over a period of one year from September 2001 to August 2002 on generation, composition, cost of collection, transportation and disposal of MSW.

*Environmental costs*

There is a dearth of environmental cost studies particularly in the Indian context. In the absence of environmental cost studies in the Indian context, figures for environmental cost per ton of different materials are taken from a study carried out for California, USA (CIWMB, 1991). For the purpose of the current study environmental costs are approximated using the composition of waste of Mumbai. Details of the estimation are shown in table 3. Since the environmental cost of a developed country will be different from a developing country, using environmental cost figures of a developed country for Mumbai imposes limitations on the current study. There is a need to carry out further research in this direction.

*Economic costs*

The various economic costs associated with sanitary landfill such as collection, operation, disposal and land are taken from a study done by

Table 4. *Transportation cost per ton per km*

| | *Type of vehicle* | | | | |
|---|---|---|---|---|---|
| | *Compactor* | *Dumper placer large* | *Dumper placer small* | *Dumper* | *Truck* |
| Capital cost/shift in '000 Rs. ('000 $) | 222 (5) | 95 (2) | 68 (1.6) | 88 (2) | 56 (1.3) |
| Labor cost/shift in '000 Rs. ('000 $) | 1,850 (43) | 450 (10) | 450 (10) | 450 (10) | 1850 (43) |
| Spares cost, garages & sheds/shift in '000 Rs. ('000 $) | 433 (10) | 185 (4) | 132 (3) | 172 (4) | 108 (2.5) |
| Fuel & oil cost/shift in '000 Rs. ('000 $) | 308 (7) | 1346 (31) | 1346 (31) | 538 (12) | 269 (6) |
| Overhead cost/shift in '000 Rs. ('000 $) | 563 (13) | 415 (9.5) | 399 (9) | 250 (5.7) | 457 (10.5) |
| Average load/shift (ton) | 7,500 | 2,250 | 1,150 | 4,000 | 4,500 |
| Km/shift | 50 | 250 | 250 | 100 | 50 |
| Cost/ton/km in Rs. ($) | 9 (0.20) | 4 (0.1) | 8 (0.18) | 4 (0.09) | 12 (0.27) |
| Average cost/ton/km in Rs. ($) (weighted average) | 7 (0.16) | | | | |

*Note*: Annualised capital cost is calculated by the MCGM by considering life of vehicles between 15 to 20 years and 10 percent discount rate. Vehicles working time is divided in three shifts, morning shift, afternoon shift and night shift. One shift is of three hours 51 minutes duration (Coad, 1997).
*Source*: MCGM, SWM department (project division).

Yedla and Kansal (2003)[2] for Mumbai. Cost of transportation of waste per ton per kilometre is estimated using data provided by the MCGM and is reported in table 4. Cost of collection, operation, transportation and land, associated with community and mechanical compost plant is estimated by Rathi (in press).

**Optimal solution**

The optimization model is solved using BDMLP solver in GAMS. Table 5 gives different costs and benefits considered to obtain the optimal solution. The following assumptions are made to obtain the optimal solution:

1. Households segregate waste into organic and recyclable material and there would be no additional cost associated with it.
2. Volume reduction factor for composting assumed to be 0.25.
3. Based on the study carried out by Beukering *et al*. (1997) the number of rag pickers in Mumbai for the year 2000–01 is estimated to be 26,444 to 59,500. Each rag picker picks up 12 kg of waste everyday (UN, 1997). This works out to a recovery rate of 40 to 87 per cent for recyclable material. For the current study an average recovery rate of 64 per cent for recyclable material is assumed for sanitary landfills.

[2] Kansal is the maiden name of Sarika Rathi.

Table 5. *Cost and benefit figures used to obtain optimal solution*

| *Cost/benefits* | *Sanitary landfill* | *Community compost plant* | *Mechanical aerobic compost plant* |
|---|---|---|---|
| | | Rs./ton ($/ton) | |
| Cost of collection | 950 (22) | 0 | 950 (22) |
| Cost of transportation* | 7 (0.16) | 0 | 7 (0.16) |
| Cost of operation | 328 (7.5) | 562 (13) | 526 (12) |
| Cost of land | 380 (8.7) | 559 (12.8) | 455 (10) |
| Environmental cost | 790 (18) | 307 (7) | 307 (7) |
| Revenue from recyclable material[a] | 211 (4.8) | 211 (4.8) | 211 (4.8) |
| Revenue from compost | 0 | 244 (5.6) | 244 (5.6) |

[a]: Average value of recyclable material is considered.
*: Values in Rs./ton/kilometer

The optimal strategy in this case is, all waste is processed at community compost plants and only inert material is transported to dump sites. Hence, community compost plant becomes the dominant option. Here community employees collect segregated waste from households. Recyclable material is sold to wholesalers and organic material is composted and then sold in the market. All inert material goes to the municipal bins, which is later transported by the MCGM to disposal sites. Figure 1 gives a graphical representation of the optimal solution.

**Sensitivity analysis**

Sensitivity analysis is conducted for collection cost, land cost, environmental cost and revenue from recycling material and compost. Different scenarios created from the analysis are as follows:

1. **Scenario I:** Introducing cost for segregation of waste with community participation.
2. **Scenario II:** This scenario assumes that there is no revenue obtained from compost.
3. **Scenario III:** Environmental costs associated with all the waste management options are neglected.

*Scenario I*

Segregation of waste at source is not costless. People have to be educated and motivated to segregate waste. Source segregation requires some infrastructure investment to facilitate the process of source segregation. Under scenario I a collection cost of Rs. 700 ($16) per ton is imposed for the community compost plant. Collection cost figure is considered from a study done by Najm *et al.* (2002). Table 6 shows different costs and benefits considered for scenario I. Under this scenario, all waste is processed at community compost plants and only inert material is transported to sanitary landfills.

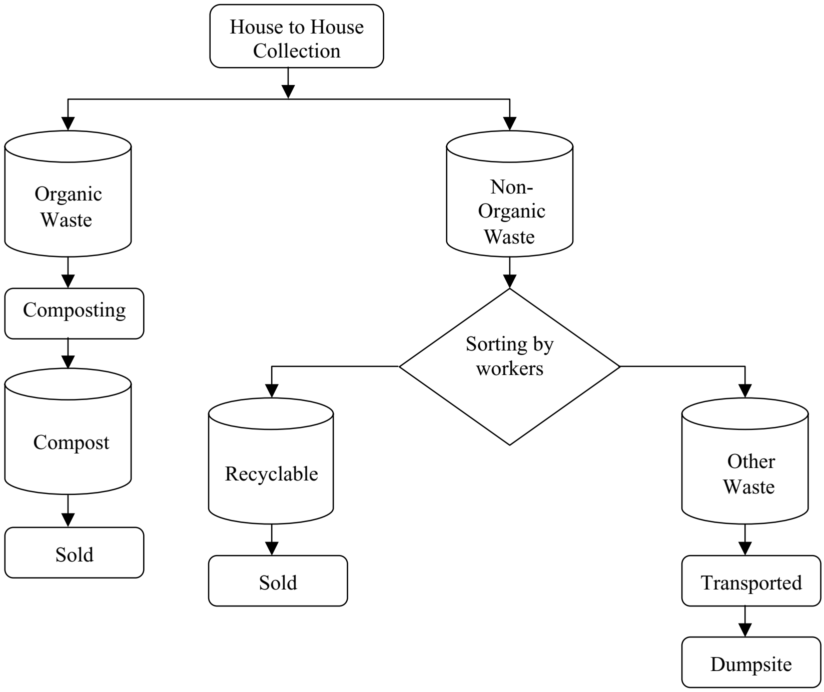


Figure 1. *Optimal waste management strategy*

Table 6. *Cost and benefit figures used to generate scenario one*

| *Cost/benefits* | *Sanitary landfilling* | *Community compost plant* | *Mechanical aerobic compost plant* |
|---|---|---|---|
| | | Rs./ton ($/ton) | |
| Cost of collection | 950 (22) | 700[a] (16) | 950 (22) |
| Cost of transportation* | 7 (0.16) | 0 | 7 (0.16) |
| Cost of operation | 328 (7.5) | 562 (13) | 526 (12) |
| Cost of land | 380 (8.7) | 559 (12.8) | 455 (10) |
| Environmental cost | 790 (18) | 307 (7) | 307 (7) |
| Revenue from recyclable material | 211 (4.8) | 211 (4.8) | 211 (4.8) |
| Revenue from compost | 0 | 244 (5.6) | 244 (5.6) |

[a]: community collection cost figure taken from Najm *et al.* (2002).
*: Values in Rs./ton/kilometer.

*Scenario II*

There are many bottlenecks associated with the revenue from compost. There is a problem with the marketability of compost produced from MSW and it is still not well accepted in the market for various reasons. In scenario two we assume that there is no or negligible revenue associated with

Table 7. *Cost and benefit figures used to generate scenario two*

| *Cost/benefits* | *Sanitary landfill* | *Community compost plant* | *Mechanical aerobic compost plant* |
|---|---|---|---|
| | | Rs./ton ($/ton) | |
| Cost of collection | 950 (22) | 700 (16) | 950 (22) |
| Cost of transportation* | 7 (0.16) | 0 | 7 (0.16) |
| Cost of operation | 328 (7.5) | 562 (13) | 526 (12) |
| Cost of land | 380 (8.7) | 559 (12.8) | 455 (10) |
| Environmental cost | 790 (18) | 307 (7) | 307 (7) |
| Revenue from recyclable material | 211 (4.8) | 211 (4.8) | 211 (4.8) |
| Revenue from compost | 0 | 0 | 0 |

*: Values in Rs./ton/kilometer.

compost produced from MSW. Table 7 gives the cost benefit matrix used under this scenario. In scenario two all waste is processed at community compost plants and only inert material is transported to sanitary landfills.

*Scenario III*

In scenario three, the following assumptions are made.

1. Cost of segregation of waste with community participation is Rs. 700 ($16) per ton.
2. No revenue is incurred from compost.
3. Environmental costs associated with all the options for waste management are neglected.

Under scenario three the optimal strategy is changed. In this scenario all waste goes directly to sanitary landfills without being processed at compost plants. Figure 2 gives the graphical representation of optimal strategy.

*Cost of collection*

There are 24 wards in the city which are highly diversified. Cost of labour in the city wards is much higher as compared to cost of labour in suburban wards. Cost of labour which constitutes a major part of cost of collection is a very important component of waste management. Hence, in this study the optimal solution is tested for the sensitivity of cost of collection. Table 6 gives an account of various costs and benefits used to check sensitivity of cost of collection of community compost plants. It is found that, till the cost of collection is Rs. 950 ($22) per ton, the community compost plant remains as a dominant option. At a collection cost of Rs. 1000 ($23) per ton, 8 per cent of waste starts getting processed at an aerobic compost plant. As soon as cost of collection reaches Rs. 1100 ($25) per ton, all waste is processed at aerobic compost plants. Figure 3 illustrates change in waste management strategy with increasing cost of collection for community compost plants.

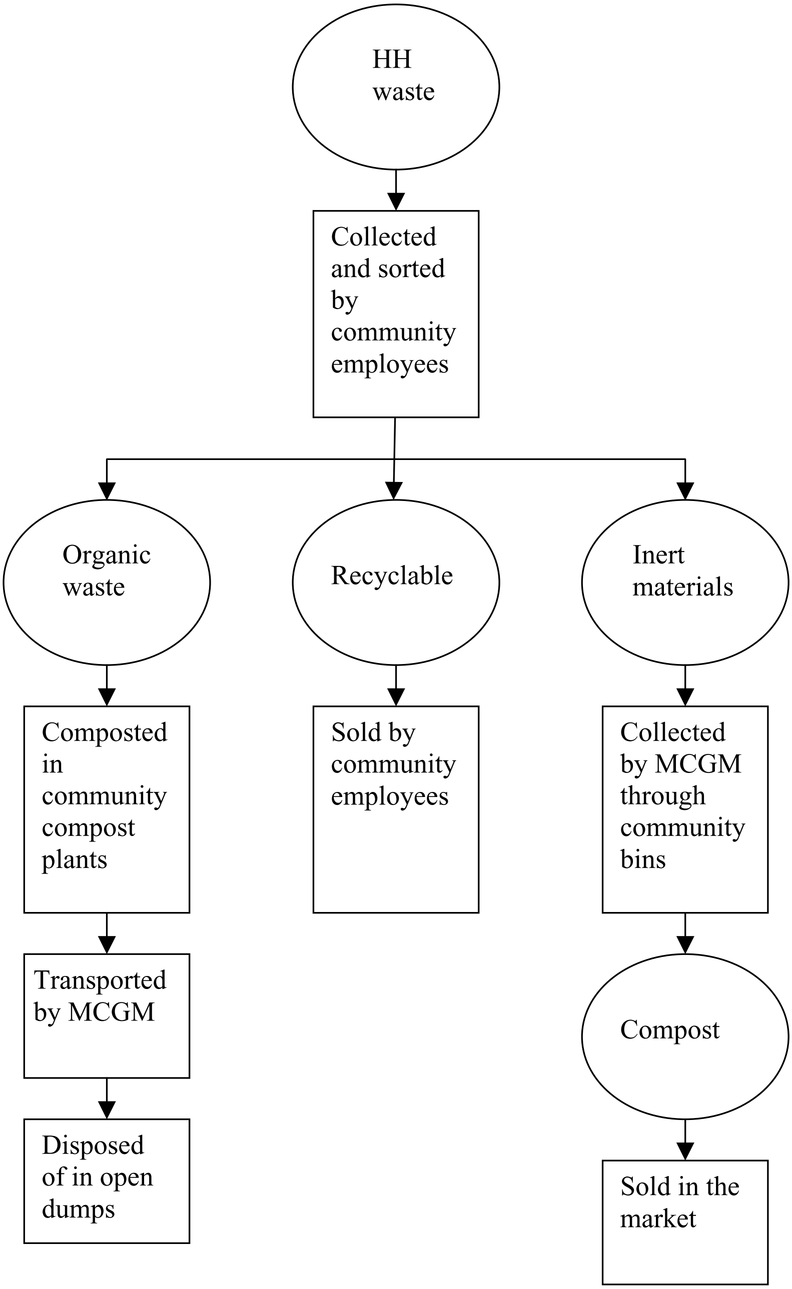


Figure 2. *Waste management strategy under scenario three*

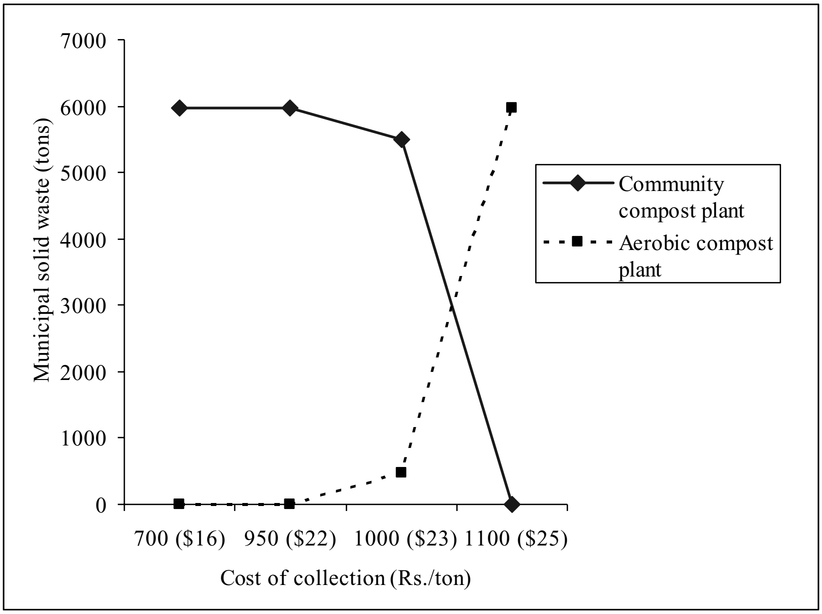


Figure 3. *Change in waste management strategy with increasing cost of collection*

**Land cost**

Land is extremely scarce and expensive in a metropolitan city like Mumbai. Moreover, the cost of land varies significantly from ward to ward. Hence, it will be of interest to see the change in waste management strategy with the change in cost of land. In this section sensitivity of operation and land cost for community compost plants is tested. Here, the cost of collection for community compost plants is assumed to be Rs. 700 ($16) per ton, and other costs considered are as given in table 6. If operating cost of community compost is kept at Rs. 562 ($13), increasing the cost of land to as high as Rs. 1400 ($32) per ton, then it is found that an aerobic compost plant is preferred over a community compost plant. Figure 4 shows the change in waste management strategy with the change in cost of land.

**Conclusions**

Mumbai, a growing metropolitan city, generated 6256 tons of waste per day in 2001. The increasing quantity of waste and limited capacity of the MCGM makes MSW management a critical issue. The MCGM spent 61,435 million Indian rupees (1413 million dollars) in 2001–2002 towards MSW management and still failed to keep the city clean. There is increasing evidence of successful participation of community and private sector in MSW management. Since the MCGM has failed to meet the increasing demand for MSW management services, there is a need to integrate the role of different stakeholders involved in waste management. In this paper, a linear programming model has been developed to design an integrated

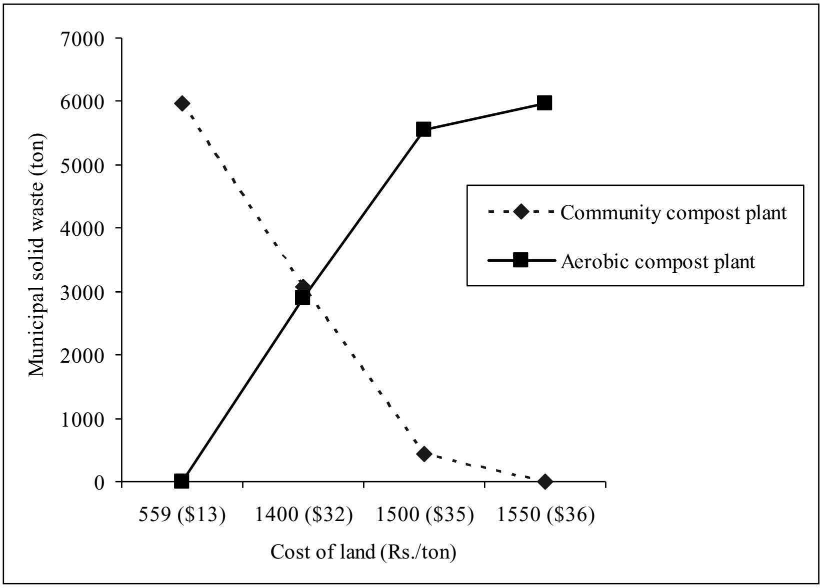


Figure 4. *Change in waste management strategy with an increasing cost of land*

waste management strategy for Mumbai taking into account different economic and environmental costs of the waste management system. In order to integrate the role of different stakeholders, different options considered for an integrated waste management strategy are community compost plant, aerobic compost plant and sanitary landfill.

The optimal solution of the model indicates community compost plants are the best option whereas sanitary landfills are indispensable for waste management in Mumbai. Further, three scenarios are constructed to test the optimal solution under various situations. The optimal solution is based on the assumptions of no cost of segregation of waste at the household level, revenue recovery from compost and considerations of environmental costs. However, in reality segregation of waste at the household level requires time and involvement from households. Further, the MCGM does not take into consideration the economic value of organic materials and environmental costs associated with different options of waste management. Scenario three is developed under the assumptions that there is a cost associated with segregation of waste at the household level, no revenue recovery from compost and neglect of environmental costs. As the model correctly predicts, under this situation sanitary landfill becomes the optimum solution. Currently the MCGM disposes of all waste collected from different wards through sanitary landfill. To improve the current situation of waste management in Mumbai there is a need for policy makers to carefully select the waste management strategy considering various economic and environmental costs and benefits involved in it.

There are 24 municipal wards in Mumbai, all of them highly diversified in terms of cost of labour and land. In city wards cost of labour and land is very high as compared to suburban wards. Hence, optimum waste management strategy may differ in wards depending on the cost of labour and land. Sensitivity analysis demonstrates that as soon as cost of segregation and collection goes above Rs. 700 ($16) per ton of waste, an aerobic compost plant is preferred. Sensitivity analysis of cost of land demonstrates that as land cost increases and reaches Rs. 1400 ($32) per ton of waste, an aerobic compost plant is preferred over a community compost plant. It can be inferred from the sensitivity analysis that the cost of land and labour can influence the MSW management strategy. This study suggests the need for decentralization of local governance and an active cooperative working mechanism amongst local government, private sector and civil society for better MSW management. Moreover, there is a need for local government to design an appropriate incentive structure in order to involve communities in waste management. However, it will be interesting to carry out a spatial analysis of waste management for different wards to see how optimum waste management strategy will differ in different wards.

In the absence of environmental cost studies in the Indian context, data on environmental costs of waste management are taken from a study done for California, USA. Cost figures may need to be revised upwards or downwards if environmental cost from India or other developing countries is used instead of the California figures. Since environmental cost of a developing country will be different from a developed country, this approximation imposes a limitation on the current study. It points to the need for carrying out further research in the direction of estimating environmental costs of waste management for Mumbai.

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