

ABSTRACT

The production of waste is an unavoidable consequence of modern civilization. The lack of resources, space, high population growth rates, and outdated methods used in developing countries has led to an inefficient Solid Waste Management (SWM) system. As a result, pollutant production rates are rising on a global scale. The unplanned and ongoing expansion of metropolitan areas makes Municipal Solid Waste Management (MSWM) more and more costly and complicated. An Integrated Solid Waste Management (ISWM) system must be implemented instead of the current dumping system of municipal solid waste to reduce the impact of several pollutants and to achieve sustainable development.

To measure the eco-friendliness of MSWM activities, an inventory of pollutants and their quantitative environmental impacts in different impact categories must be determined. Considering the current data availability, the Life Cycle Assessment (LCA) is one of the most appropriate tools for assessing the environmental impact of MSWM systems in order to determine the best MSWM strategies.

The literature review shows a lack of research on the total pollutants generated by the MSWM system, the quantitative effects of the pollution using LCA and the resulting optimal cost solution, especially in Kolkata, a metropolitan city in India, a developing country. In this study, an effort has been made to assess and minimize the Potential Environmental Impact (PEI) of the MSWM system, practiced in metropolitan cities of developing countries, using LCA methodology considering the cost-effectiveness and quantitative environmental impact, maintaining all system operational constraints.

A generic linear programming (LP) model has been developed while considering all components and cost of MSWM system with possible pollutants generation and PEI for the Kolkata. The quantitative impacts of MSWM activities have been evaluated with the help of a systems approach i.e. LP model with the LCIA methodology of LCA. The LP model is run for different cases to find out the eco-friendliness of the activities considering the cost and PEI and compared. To generate the LP equation, a software program was developed in LINDO V9.0 optimization software.

The model for the MSWM system of the study area, Kolkata, includes gaseous emissions from the transportation sector, incineration plant, composting facility, and landfill, as well as liquid pollutants from landfill leachate. The model is run for different scenarios of existing SWM and proposed ISWM systems and compared to determine the suitability of the system in terms of cost-effectiveness and eco-friendliness.

Kolkata Municipal Corporation (KMC) currently generates ~4600 MT of Municipal Solid Waste (MSW) per day. At present, the source segregation partly started in Kolkata. The informal rag pickers collect about 5% of the recyclables from waste at the households' level, containers, and compactor locations. 95% of the waste goes to the Dhapa landfill from which ~4.21% of the materials was further separated. Thus, only around 9.21% of the total waste is recovered and recycled and the remaining waste is dumped in a landfill with silt. At present the landfill lacks a gas collecting facility, leachate management system, and liner.

The model has been validated with the actual KMC datasheets of 2022. Excellent results are obtained from validating the LP model for the present scenario which shows that ~5% cost minimization, is possible. Consider that departmental vehicles transport 85% of total waste; whereas hired vehicles transport 15%. The total PEI came out to be 8.37×10^{-3} for the existing MSWM system of Kolkata.

The model is then implemented in both free modes, without vehicle-optimization and with vehicle-optimization for the existing SWM system. Optimizing the number of departmental vehicles results in a ~52.6% decrease in total transportation costs and a ~47.5% reduction in total SWM costs compared to the existing system without vehicle-optimization. However, the total incentive cost of vehicle-optimization is significant; in this situation, all departmental vehicles are required to make more trips than their assigned minimum. However, the PEI remains the same in both circumstances.

The result implies that the total emission of the departmental vehicle is ~90%. The departmental vehicles carry ~90% of the total waste in restricted condition. In case of the hired vehicles, the total emission is ~10% which carry ~10% of the total waste. The quantity of total gaseous pollutant emitted from the existing MSWM system of Kolkata is ~269641 MT per year.

The total gaseous pollutant generation contributed by the transport sector is around 4733 MT/year (~2%). Total contribution of CO₂ emission is the highest (99.1%). NO_x generation is the second largest (0.475%) which is higher than CO (0.26%) and HC (0.073%). SO₂ emission (0.022%) is much less compare to NO_x due to the stringent permissible sulphur percentage in diesel fuel.

The total gaseous pollutant emission from landfill in existing MSWM system of Kolkata is 264908 MT per year, which covers ~98% of the total gaseous pollutant emission. The major pollutants from landfill gases are CO₂ and CH₄, causing rise of global temperature. The percentage of CO₂ is around 73% whereas the CH₄ is about 27% of landfill gas generation. The percentage contributions of NH₃-N, and Cl to total liquid pollutants generation from landfill leachate in the present MSWM system are 29.3%, and 70.5%, respectively. The transport sector and landfill provide 12% and 88% of total PEI, respectively. The liquid pollutants of landfill account for approximately 52% of total PEI, while gaseous pollutants accounting for the remaining 36%. Among all the PEI sub-categories, HTPE is the highest (~29%) followed by ATP (~27%), HTPI (~23%), and TTPL (~8%), w.r.t. total PEI.

The proposed ISWM systems include three transfer stations on each side of KMC's perimeter, each with three material sorting, incineration, and composting facilities. Three specialized engineered landfill (ELF) sites are being considered for the disposal of process rejects, inerts, and silt. The validated model is then used to simulate the proposed ISWM system, both with and without departmental vehicle optimization. Without vehicle optimization, the system would cost Rs. 44,69,858 per day. The overall daily cost for ISWM systems with vehicle optimization is Rs. 20,07,230. When compared to the cost of the existing MSWM system without vehicle optimisation conditions, there is a 17.88% decrease in overall SWM cost and a 1.28% reduction in ISWM transportation cost. Although ELF includes a costly leachate collection infrastructure and a liner system, it

reduces landfill costs by approximately 18% due to lower material volume. However, without vehicle optimisation, ISWM led to a 12% increase in incentive costs.

Vehicle optimization on the proposed ISWM system reduces overall SWM costs by approximately 63% for unoptimized and 30% for optimized existing systems. It was discovered that incentive expenses had increased by 1.8%. Silt and process rejects are deposited far from the city, increasing transportation costs by 2.54%.

Waste sorting, composting, and incineration increase cost of operation by approximately 41% over net SWM costs without vehicle optimisation. Selling recycled materials, compost, and power generates significant revenue, accounting for approximately 37% of total expenses without vehicle optimisation and 57% with vehicle optimisation of proposed ISWM systems. Composting operations generate approximately 77% of revenue, while incineration yields about 20%. Selling recyclables only accounts for ~3% of the total due to the low volume of recyclables in developing nations' MSW.

The total cost is reduced by 55.1% and the transportation cost decreases by 50.8% in vehicle optimization condition w.r.t vehicle un-optimized condition of ISWM systems. Departmental vehicles contribute 90% of pollution and share ~81% of waste.

The proposed ISWM systems emit approximately 4.5×10^5 MT of gaseous pollutants annually. The transportation sector contributes 3637 MT (~0.8%) of pollutants per year. Annually, incinerators emit around 2.25×10^5 MT (50%) of gaseous pollutants, while composting plants generate approximately 2.22×10^5 MT (49.2%). The proposed ISWM system emits approximately 67% more gaseous pollutants than existing MSWM systems, primarily from incineration and composting. The overall pollutant emissions from landfill leachate are reduced by 99.7% when compared to the existing MSWM system due to improved leachate quality and less inert waste disposed in the ELF site with leachate treatment facilities of proposed ISWM systems.

In unoptimized vehicle conditions, approximately 44% of total waste enters the east transfer station, 19% enters the north transfer station, and 37% enters the south transfer station. To mitigate the earlier stated distribution discrepancy to avoid overburden, waste is transported in a 3:4:3 ratios to the North, East, and South transfer stations using the proposed ISWM system in vehicle-optimized condition. In this scenario, 40% of the waste is transferred to the east transfer station, 30% to the north transfer station, and the remaining 30% to the south transfer station.

The proposed ISWM system has a total PEI of 6.05×10^{-3} , resulting in a 27.7% reduction over the existing MSWM system. The PEI results show that incinerators account for around 69.1% of PEI under vehicle-optimized conditions, followed by composting at ~29.7% and transportation at ~1%. Landfilling accounts for only about 0.2% of total PEI. The proposed ISWM systems reduce GWP by approximately 68.3% when compared to the existing system, which comprises mainly of CO₂ and CH₄.

The local category accounts for approximately 98.9% of PEI in proposed ISWM systems. NO_x accounts for the largest percentage of PEI (~58.37%) among gaseous pollutants, followed by CO₂ (18.25%), SO₂ (16.85%), and CH₄ (6.28%).

The PEI comparison between BS-IV and BS-VI standards in the transport sector of a vehicle-optimized ISWM system shows that the transportation sector's PEI contribution can be reduced by 79.2%. In terms of PEI contribution from the transportation sector, AP shows a reduction of around 97%, while HTPE and TTPG show a reduction of approximately 79.2% in BS-VI standards, due mainly to lower SO₂ and NO_x emissions. Implementing BS-VI standards over BS-IV, the vehicle-optimized proposed ISWM system can lower overall PEI from various activities by 0.66% only because the effects of transport sector emissions in total PEI are lessened.

The model is also applied to the proposed ISWM systems with two operational ELF's instead of three. The overall costs of the vehicle-optimized ISWM system with two operational ELF's vary very slightly from the three dumpsites of the system. The overall cost of SWM increases by 1.87%, 4.16%, and 6.32% for the ES, NS, and NE configurations, respectively. The landfilling cost has also varied between 2% and 1% of the proposed ISWM system's normal vehicle-optimized condition. In comparison to the vehicle-optimized ISWM system, each of the two ELF configurations results in a net increase in pollutant emissions from the transportation sector ranging from a maximum of 30% to a minimum of 14%. Because departmental and hired vehicles travel further from boroughs to deposit waste and silt in transfer stations, the pollutant generation in two ELF configurations exceeds that of three ELF designs. The total PEI for the NS, NE, and ES configurations increased by 0.33%, 0.17%, and 0.17%, respectively, as a result of the generated pollutants.

Sensitivity analysis was performed under a variety of scenarios. Variation of $\pm 1\%$ in total waste generation results in $\pm 0.48\%$ in total SWM costs and $\pm 0.99\%$ in total PEI. When fuel prices vary by $\pm 5\%$, total SWM costs vary by $\pm 0.86\%$.

For every $\pm 10\%$ variation in CO₂, the total PEI varies by $\pm 1.8\%$. A 10% change in NO_x emission rate results in a $\pm 6\%$ change in total PEI. The variation in the emission of liquid pollutants has insignificant effects. The model analysis demonstrates that incorporating numbers of transfer stations and ELF in different directions of the city lowers both MSWM cost and PEI.

The model shows that the vehicle-optimized proposed ISWM system, along with the transfer station, provides an ideal combination of optimal cost and least PEI. The model also shows that in comparison to Waste-to-Energy incinerators, composting is highly profitable and there is a major impact on the SWM cost.

The model studies the pollution-minimization potential of existing and proposed ISWM systems, showing encouraging results. It also shows that the LCIA methodology of LCA can be successfully applied and used as a decision support tool to evaluate various waste management alternatives and obtain the optimal cost and PEI combination for the transporting, treatment, and disposal of municipal solid waste.

Though the research focuses on Kolkata city as the study area, and the datasets pertain to that of KMC, yet, it is important to note that the solutions suggested by the model are quite generic and the solutions can easily be implemented in any city in a developing country like India, thus promoting a development which is both environmentally and economically sustainable.