Life Cycle Assessment Model for Integrated Solid Waste Management

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Abstract

Solid waste management is an important issue in today's world as it deals with (i) budget allocations of local municipality (ii) public acceptance and (iii) adverse impacts on environment. A careful observation of the material flow in a Solid waste management facility reveals a few interconnected activities. They are (i) waste treatment and disposal results in transfer of material flow from one source to another or one phase to another (ii) material flow is continuous (iii) the environmental burdens (or impacts) associated with material transfer should be accounted for (iv) a close loop exists among the interconnected activities in the material transfer. The present study focuses on these aspects and revealed an interrelation ship among the activities that can be understood using system's approach. Landfilling of solid waste is a waste management option triggering a series of actions. The impacts of this activity are analyzed using Life Cycle Assessment (LCA) approach. A methodology for allocating of environmental loads among different functions within a system boundary is proposed using the example of landfilling of solid waste.

1. Introduction

Solid Waste Management (SWM) in Developing Countries is becoming aggravated in view of the continual increase of their population growth [4,9]. Effective and comprehensive SWM practices are yet to emerge in these countries due to technical-, social-, administrative-, financial- aspects etc. Open dumping is the common mode of disposal that is followed in majority of the places in Developing Countries, in general and India, in particular. Bhide [3] observed that 90% of the landfills in India are mere open dumps. Serious consequences of pollution problems can be experienced due to indiscriminate solid waste disposal practices. The Developed Countries have recognized the limitations of the end-of-pipe solutions and are adopting the preventive approach as a complement to control the treatment options for waste management [16]. Pollution prevention through waste minimization aspects should become the primary focus in Developing countries to avoid environmentally costly mistakes. The specific goals of each community for implementing SWM plans however depend upon the targets they would like to address such as minimizing the land required for landfill, volume reduction alternatives etc.

The environmental implications of product and service systems can be analyzed using Life Cycle Assessment (LCA) approach [5,6]. LCA is a methodology used to predict the impacts of the utilization of the world's raw material and energy resources [13]. The LCA framework helps in assessing potential impacts arising out of an activity and the subsequent shifting of environmental burdens among the receptor media (viz., air, water, land etc.) to another stage of the life cycle [1, 8, 15, 18]. The available studies [14, 19] primarily focused on different aspects of SWM and usage of LCA for SWM. Further, Solano et al., [17] studied a large number of unit processes with numerous combinations of waste flow paths in SWM; Haith [11] focused on materials balance in solid waste management targeting on only the streams that enter the landfill where only the methane emissions are considered as output emissions from the landfill; Finnveden[10] considered the time aspect in estimating landfill emissions and importance of systems analysis in waste management systems; Harrison et al [12] developed a decision support system accounting for LCI emissions from various stages of collection of solid waste; Craighill and Powell [7] applied LCA to two cases (i) comparison of two methods of collecting and sorting recyclable waste and (ii) comparison of six waste disposal alternatives using environmental, social and economical criteria.

The LCA approach is applied in the present study to the problem of solid waste disposal, in general, and landfilling of solid waste in particular, to analyze the impacts on the receptor sources. Emphasis is given to the cyclic phases of material/pollutant transfer occurring at various stages of solid waste disposal and modeling the stages using LCA.

2. Life Cycle Assessment Approach

A SWM facility comprises of a number of activities such as waste collection and sorting, its transfer and transport, proper treatment, recovery, disposal and operations such as sorting, sieving, material recovery, composting, landfilling, incineration etc. The objective of a SWM facility is to ensure proper treatment and disposal of solid waste. The solid waste will further generate waste streams during its movement and material conversion in the SWM facility. For example, the leachate generation from landfill, air pollution during incineration of solid waste etc. are different forms of the waste that are generated from solid waste. The study of the impact of these waste streams on environment is considered. The contributions from the gaseous and particulate emissions from incinerator, for example, on the natural processes occurring in atmosphere such as precipitation will initiate a cycle in the local environment. The environmental impacts of the activities connected with waste management must be closely studied. For example, recycling attempt will reduce material consumption but it should also be understood that whether this savings in material will yield positive impacts on environment when the impacts of activities related to recycling efforts are also considered. The present study targets a waste management option and focuses on - (i) identifying such cycles where contributions are transferred from previous actions (ii) understanding the linkages among these cycles and (iii) suggesting a methodology for assessing the impact of these cycles on environment using a model. The study is carried out using LCA on landfill emissions as the starting point of the series of cycles. Though the available studies dealt with several issues with regard to SWM and its analysis, the study of the linkages among the various cycles and the connected impact on environment is not available. There is however a debate [10] persisting on appropriate allocation between different functions with respect to the limits of the system boundary.

LCA addresses the study of impacts on environment during several stages of material transfer during its life cycle i.e., raw material acquisition, manufacturing, transportation, use, recycle, waste management stages as shown in Fig.1. The inputs could be material and/or energy. The conceptual definition of LCA as shown in Fig. 1 is taken as basis [1] for the present study.

Waste generation occurs when a material is transferred from its raw stage to a purified (or product) stage or while it moves from one stage to another stage in a process operation. The discarded material from a process operation will also be converted as waste material. The product after its usage will be converted to waste material and is disposed off in the local environment. The waste material is recovered either in full or in part to be used back in the process operation (Refer Fig.2) as raw material.

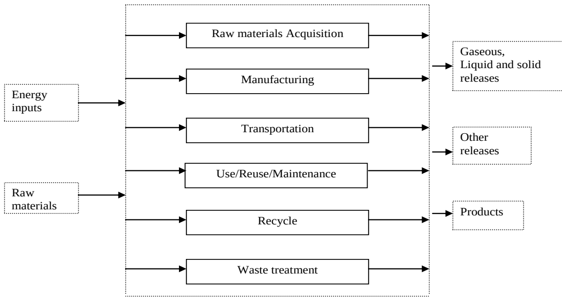

Fig.1: Typical schematic of Life Cycle Assessment (LCA)

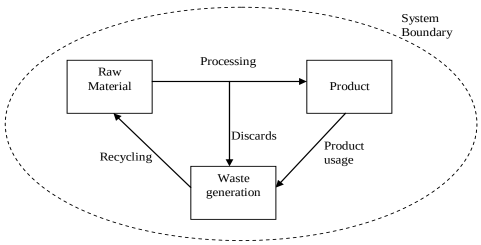

Fig.2: Relation among Raw material, Product and Waste generation in a system

If the relationship among raw material, product and waste generation is extended to the formation of the raw material from its mineral/ore (Refer Fig. 3), it may be noticed that the disposed material is consumed by biotic species in the environment which after the decay and decomposition in earth's crust will end up as minerals and ores. They are processed to get the raw material required for producing an useful product. The rejects generated during the processing of minerals/ores will end up as waste material for their further treatment.

3. Model Development

The LCA approach is now extended to the actual problem of landfilling of solid waste (Refer Fig. 4) assuming it as the starting point. The landfill produces leachate which should be treated in an Effluent Treatment Plant (ETP). The production of leachate depends on the precipitation occurring locally which is variable. The leachate at ETP is treated by adding chemicals, biomass and energy to the treatment units. The treated leachate is discharged from ETP and if it is used for on-land irrigation will result in creation of agricultural products. These products during their transport and consumption will generate solid waste that should be treated resulting in completing a cycle.

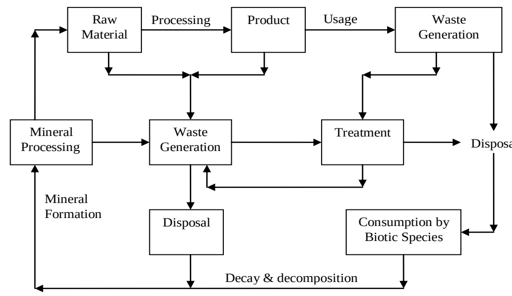

Fig.3: Typical life cycle of material flow in the environment

The sludge from ETP of leachate is to be treated and disposed off. Incinerating this sludge as it contains toxic pollutants will result in both air emissions and residue. The residue should be treated in a landfill as it is a solid waste thus completing another cycle of material movement. The air emissions from incinerator will result in contaminated precipitation in atmosphere and will end up as leachate for the landfill (another cycle). The runoff from the leachate and contaminated precipitation will be reaching the natural water sources at both surface and ground. The water when tapped for drinking should be treated in a Water Treatment Plant (WTP). The sludge (i.e., solid waste) that is generated from the WTP should be properly treated and disposed off (another cycle). The water after its consumption in the domestic and industrial sectors will end up as wastewater. This wastewater should be treated in an ETP by giving chemicals, biomass and energy as inputs. The sludge generated should be treated and disposed off properly (another cycle). As mentioned earlier, there are a number of operations in a SWM facility. A simple operation of landfilling has resulted in a significant transfer of material, forming several cycles among the events considered. It should be noted here that the material is moving within the system boundary i.e., *closed loop* and is only getting transferred from one stage to the other.

A close examination of the analysis of the events that triggered due to landfilling of the solid waste (Refer Fig.4) revealed that (i) material is transferred from one stage to other (ii) there exists a close loop within a chain of activities (iii) all the activities are occurring within the boundary of environment. It is also understood from Fig.3 that the material is being recovered in the earth's crust either fully or partially and follows the law of conservation of mass. It should be noted from Fig. 1 that the impacts occurred in a material during its life cycle can be quantified (Aelion et al., 1995). The relation-ship among the various systems present within the boundary of events is summarized (Refer Fig. 5) as below:

- The overall system will have environment as its boundary
- The system contains sub-systems where the changes are occurring
- Each of the sub-systems are further divided into small sub-sub systems depending on the activities that are considered within the sub-sub system
- The impacts of each of the systems can be quantified and carried forward
- The overall impact of the entire system depends upon the summation of the impacts from sub-systems

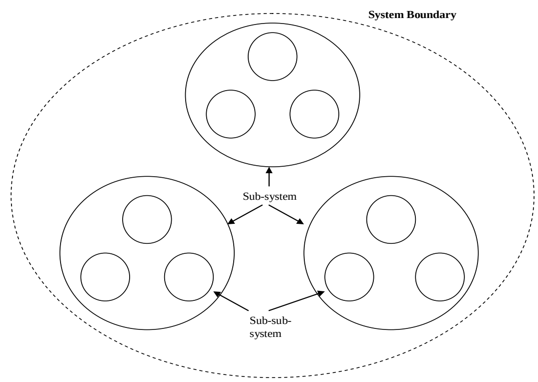

Fig. 5: Typical relationship among the systems

For example, if the overall impacts of SWM on environment are to be considered, first the activities or operations (such as landfilling) in SWM leading to environmental impact should be identified. The impacts that are triggered due to the series of actions resulted should be identified. The summation of all these impacts will give a comprehensive impact scenario of SWM on environment.

Once the impacts from all the sub-systems are identified, they can be quantified using the *micro-level* methodology presented below:

- Identify the first stage of material transfer. For example, Materials M1 and M2 getting converted to products P1, P2 at the end of stage-I and P3 at the end of stage-II (Refer Fig.6). The wastages from the process are W1 and W2 at the end of stage-I and stage-II respectively. A system boundary is drawn around stage-I and quantities are estimated based on mass and/or energy balance. Now the products P1 and P2 of stage-I will become the raw materials for stage-II for performing the calculations.
- Consider the net-sub-system (Refer Fig. 6) having M1 & M2 as raw materials, P3 as product and W1 & W2 as waste materials from the process. Transfer the calculations performed in the above step to obtain the necessary information as desired.

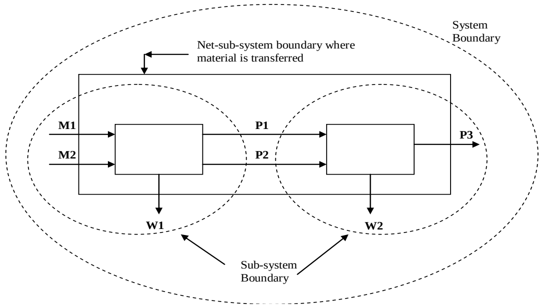

Fig.6: Model proposed for estimating impacts for integrated solid waste management

The example that is shown in Fig. 6 can be taken as equivalent to that of a sub-sub system as shown in Fig. 5. Impacts from all the sub-sub systems can be similarly added together to get the overall impact due to a specific activity on the system i.e., environment. Using this model, a wide range of environmental impacts due to any activity can be estimated.

Babu and Ramakrishna [2] applied life cycle inventory analysis, which is a part of LCA, for prediction of environmental impacts due to adsorbent preparation using saw dust using a similar model approach given in Fig.6. Adsorbent is prepared in laboratory using saw dust for waste water treatment. The authors considered only the material balance in this regard in terms of raw saw dust, distilled water and acids (HCl and H_2SO_4) as raw materials M1, M2, and M3. The adsorbent preparation occurred in two stages stage-1 and stage-2 which are associated with waste realease in each of the stages. The contributions of P1, P2, W1, W2 and P3 are calculated based on laboratory tests while adsorbent prepared is considered as P3. The eco vectors and total production load per unit of product (adsorbent) within the system boundary are calculated. Similar calculations are performed for other waste and non-waste emissions in the process. It is concluded that per eack kg of finished product (i.e., P3), (i) 11.54 kg/kg of raw material (M1) is required (ii) 79.54 kg/kg of distilled water (ie., M2) is required (ii) 2.45 kg/kg of saw dust rejects (i.e., W1 & W2) are obtained for the studies conducted. In a similar manner, the contributions of each subsystems can be computed using this model and added to obtain the overall impacts from the problem.

Summary and Conclusions

The transfer of waste as a material into environment in different forms should be accounted for when the overall impact of a waste management activity is analyzed. The environmental impacts associated with a waste management activity are studied by considering landfilling of solid waste as an example. Life Cycle Assessment methodology is applied to analyze the interrelationship among the various impacts associated with landfilling of solid waste in environment. A model is suggested based on system's approach for allocating the environmental impacts due to an activity within a system's boundary using a casestudy where the model is succesfully applied for preparation of adsorbent in wastewater treatment.

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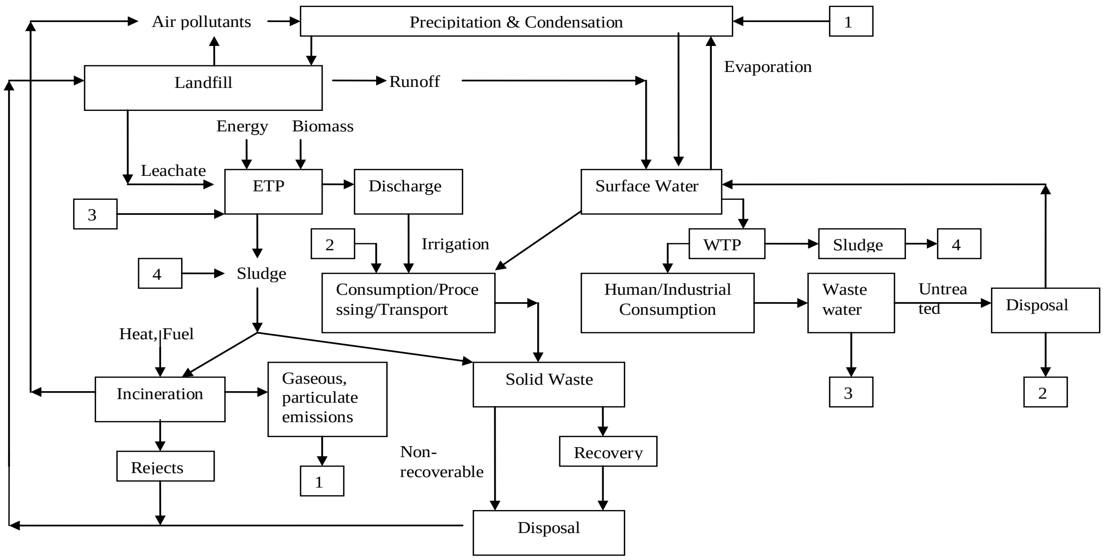

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