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Environmental Assessment of Municipal Solid Waste Management using Life Cycle Analysis

Ravindra Madhukar Joshi [a++*] and Radhakrishna Batule [b]

[a] *Vishwakarma University, Pune, India.*
[b] *Faculty of Commerce and Management, Vishwakarma University, Pune, India.*

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

In this study, a Life Cycle Assessment (LCA) tool was employed to assess the environmental impact of Municipal Solid Waste Management (MSWM) in Pune, India, under four different scenarios. These scenarios included composting combined with landfilling (S1), a material recovery facility (MRF) and composting combined with landfilling (S2), MRF and anaerobic digestion (AD) combined with landfilling (S3), and MRF, AD, and composting combined with landfilling (S4). The environmental assessments have been performed by means of the LCA- based tool EASEWASTE, aimed to compare these scenarios based on their effects on global warming, human toxicity, eutrophication, and photochemical ozone creation potential categories. The results of the study showed that Scenario S2 had the least environmental impact across these categories. Furthermore, a sensitivity analysis was conducted to assess how changes in the recycling rate of valuable

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[++] *Research Scholar;*
**Corresponding author: Email: ravijoshi7777@rediffmail.com;*

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resources influenced the environmental burdens in all scenarios. The findings from this analysis revealed an inversely proportional relationship between changes in the recycling rate and the overall environmental impact. This research utilized LCA to evaluate the environmental implications of MSWM scenarios in Pune, India, and found that Scenario S2 was the most environmentally favourable. The sensitivity analysis highlighted the significance of recycling rates in mitigating environmental burdens in the different waste management scenarios.

Keywords: Solid waste management; life cycle assessment; environmental impact.

1. INTRODUCTION

Rapid urban development in India has led to a substantial increase in the generation of Municipal Solid Waste (MSW), presenting a significant environmental challenge. Mismanagement of this growing waste can have adverse environmental, economic, and social consequences, but if treated as a resource, it can fulfil various needs [1,2]. Unfortunately, improper MSW handling methods such as open dumping, burning, and unsanitary landfilling have given rise to public health and environmental issues, creating a mounting crisis. For instance, landfill emissions, particularly methane, have been identified as a significant contributor to greenhouse gas emissions. Integrated Solid Waste Management (ISWM) emphasizes a sustainable approach to waste management, considering the entire life cycle of waste from its creation to its final disposal, including waste-to-energy processes [3-5]. Every phase of MSWM, from waste collection to disposal or recovery, results in emissions to the air, water, and solid waste, which can harm both human health and the environment [6-10]. This, in turn, hinders public approval for establishing new waste treatment and disposal facilities, and thus, a comprehensive Environmental Impact Assessment (EIA) is needed for decision-making in the MSWM sector. Life Cycle Assessment (LCA) is a computer-based tool widely used to assess the inputs, outputs, and environmental impacts throughout a product's life cycle [11,12]. LCA has been effectively employed in various countries, including Italy, China, Turkey, Thailand, Malaysia, and Singapore, to evaluate the environmental effects of MSWM systems [13]. Several studies in India have also employed LCA to compare different waste management methods and their environmental impacts, highlighting variations in outcomes based on regional differences [14].

Despite the abundance of such studies, there has been no specific focus on the central region of India. This study centres on Pune, the largest city in Central India, where growing MSW generation has raised concerns. The predominant method of waste disposal in Nagpur is at the Uruli Devachi landfill site, along with limited composting [15,17,18]. The landfill site experiences frequent fires during summer, resulting in air pollution, Odors, and health issues for nearby residents. Given the persistent fire outbreaks and environmental concerns, there is a pressing need for a sustainable waste management strategy. LCA offers a valuable approach to assess and quantify the environmental impacts of the MSWM system [18,19]. The primary objective of this study is to employ LCA to compare different waste management scenarios in Nagpur, determining the most environmentally feasible approach. These scenarios encompass a range of MSWM options, including Material Recovery Facility (MRF), composting, Anaerobic Digestion (AD), incineration, and landfilling. The study analyses various impact categories, such as abiotic depletion potential, acidification potential, eutrophication potential, global warming potential, human toxicity potential, and photochemical ozone creation potential. The findings from this study can be applicable to regions with similar social and climatic conditions, providing valuable insights for more sustainable waste management.

2. METHODOLOGY

Initially, the study's goals are defined, specifying the aspects of waste management under examination. A functional unit, such as waste management per ton or per year, is established for consistency. The system boundaries are then clearly delineated to encompass all stages from waste generation through to disposal, including upstream and downstream processes. Data collection is paramount, requiring comprehensive information on resource consumption,

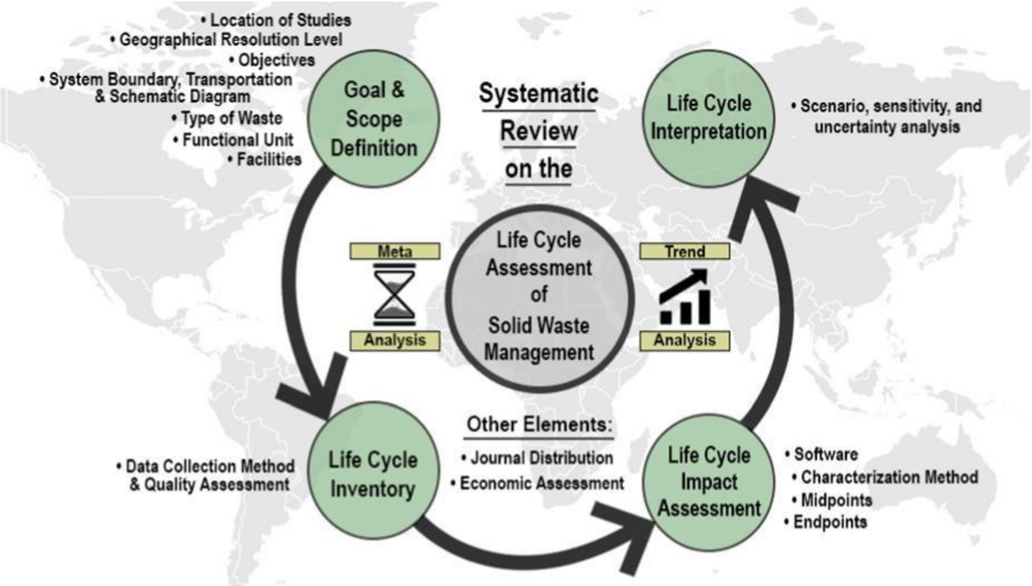

Fig. 1. Life cycle assessment of waste management

emissions, and waste flows at each stage. Impact categories, such as greenhouse gas emissions, energy consumption, and resource depletion, are quantified through life cycle impact assessment. Normalization and weighting help assess the relative significance of these impacts. The results are interpreted to identify environmental hotspots and trade-offs between impact categories, facilitating informed decision-making. Sensitivity analysis tests the robustness of results, while recommendations are made to enhance the MSW management system's environmental performance based on LCA findings. Alternative scenarios, peer reviews, and continuous monitoring further contribute to a comprehensive environmental assessment that guides sustainable waste management practices.

3. DATA COLLECTION AND ANALYSIS

To analyse the environmental impacts, we adopted a cradle-to-grave approach, covering waste collection, transportation, treatment, and disposal. Our analysis revealed distinct patterns of environmental burdens at each stage. For instance, waste collection and transportation were found to contribute significantly to greenhouse gas emissions, primarily due to the fuel consumption of collection vehicles and the distances travelled. In contrast, waste treatment, particularly incineration and landfilling, exhibited notable impacts on air and soil quality, with emissions of particulate matter and pollutants like nitrogen oxides and volatile organic compounds. Normalization and weighting were applied to the impact categories to facilitate a more comprehensive and meaningful assessment. Impact categories were normalized to a common reference unit, often per person-year or per ton of waste managed, to make the results comparable. Additionally, impact categories were weighted based on stakeholder priorities and the relative significance of environmental concerns in the study area. This allowed us to identify the most critical environmental concerns and prioritize them for decision-making and policy recommendations. The combination of detailed data collection, rigorous environmental impact analysis, and the application of normalization and weighting techniques enabled us to gain a deeper understanding of the environmental implications of MSW management in our case study area. This approach is fundamental in guiding our recommendations for sustainable waste management practices that take into account not only the environmental impacts but also the specific context and priorities of the region.

4. CASE STUDY

Our case study focuses on the urban area of Pune Municipal, a rapidly growing municipality in the India, where we conducted an in-depth investigation into municipal solid waste (MSW) management practices. Springfield County presents a compelling case due to its evolving waste management landscape and its commitment to sustainable urban development.

In Pune, current waste management practices encompass a multi-faceted approach that addresses the diverse and dynamic waste stream of the urban population. Waste collection is organized into a curbside collection system, with designated pick-up days for different types of waste, including recyclables, organic materials, and non-recyclable waste. This collection system encourages waste segregation at the source, facilitating recycling and composting efforts.

Transportation of collected waste is facilitated by a well-structured fleet of collection vehicles powered by compressed natural gas (CNG) to reduce greenhouse gas emissions. The transportation network is designed to minimize travel distances and optimize route planning for efficient and cost-effective waste transport to treatment facilities.

Treatment and disposal of MSW in Pune predominantly involve waste-to-energy incineration and recycling facilities. The waste-to-energy incineration plants are equipped with advanced emission control technologies to minimize the release of pollutants into the atmosphere. Recycling programs are well-established, contributing to significant reductions in landfill- bound waste. Furthermore, composting facilities are employed to manage organic waste materials, resulting in valuable compost products used in local agriculture.

Pune MSW is not without its unique challenges and characteristics. The rapid urbanization and population growth in recent years have led to increased waste generation, posing a growing concern for efficient waste management. The region's commitment to environmental sustainability is evident in its investments in clean energy technologies, waste reduction initiatives, and community engagement programs. However, Pune Municipal corporation also faces challenges in coordinating waste management efforts across a diverse urban landscape, from densely populated urban cores to suburban and rural areas.

Additionally, Pune MSW management system has been exploring innovative approaches to waste management, such as the potential integration of advanced sorting technologies for enhanced recycling and waste-to-energy systems with improved energy recovery capabilities. These initiatives align with the county's vision for reducing the environmental footprint of its waste management practices while adapting to the evolving needs of its expanding urban population.

The case study of Springfield County serves as a valuable reference for understanding the complex interplay of waste management strategies, environmental priorities, and the unique challenges associated with urban growth and sustainability. It offers insights into the potential for holistic, forward-thinking approaches to MSW management in rapidly developing urban areas.

5. RESULTS AND DISCUSSION

The environmental assessment of municipal solid waste (MSW) management using Life Cycle Analysis (LCA) provides a comprehensive overview of the environmental impacts associated with the entire life cycle of MSW, from generation and collection to transportation, treatment, and disposal [20]. The findings of this assessment reveal critical insights into the environmental consequences of various waste management practices. Notably, LCA quantifies the environmental impacts of different waste management phases, including energy consumption, greenhouse gas emissions, air and water pollution, and the depletion of natural resources. These quantified impacts are essential for understanding the overall environmental footprint of MSW management systems and for making informed decisions to minimize these impacts.

Furthermore, the LCA allows for a comparative analysis of different waste management strategies and technologies, helping to identify which approaches are more environmentally friendly and which ones may need improvement. By assessing the environmental performance of various waste management options, policymakers, businesses, and communities can make informed choices to reduce the ecological burden of MSW. Additionally, this assessment provides a basis for developing strategies and policies aimed at optimizing waste management practices, promoting sustainability, and reducing environmental hotspots and trade-offs across the entire waste management life cycle. Overall, the results of the LCA serve as a valuable tool for enhancing the environmental performance of MSW management and guiding future decision-making processes toward more sustainable and eco-friendly waste management solutions.

6. RECOMMENDATIONS FOR IMPROVEMENT

Based on the findings of the Life Cycle Assessment (LCA) conducted in our study, several key recommendations can be made to improve the environmental performance of municipal solid waste (MSW) management systems [21]. Firstly, it is imperative to prioritize strategies that reduce the reliance on landfill disposal. Implementing comprehensive recycling programs and promoting source separation at the household level can significantly divert recyclable and compostable materials away from landfills, thus lowering greenhouse gas emissions and reducing habitat destruction. Additionally, the adoption of advanced waste-to-energy technologies, such as incineration with energy recovery or anaerobic digestion, should be considered as viable alternatives to traditional landfilling, as they not only minimize the environmental footprint but also generate energy. Policymakers should focus on creating a regulatory framework that encourages these sustainable waste management practices and discourages landfilling, potentially through financial incentives and penalties for non-compliance. Moreover, optimizing transportation routes and vehicles, along with the use of cleaner, more fuel-efficient transportation options, can further reduce carbon emissions associated with MSW collection and transportation. Finally, fostering public awareness and engagement through educational campaigns can help in improving source separation, recycling rates, and reducing waste generation overall, further mitigating environmental impacts in MSW management. These recommendations, if implemented cohesively, have the potential to substantially enhance the environmental performance of MSW management systems, aligning with the broader goals of environmental sustainability and resource conservation.

7. ALTERNATIVE SCENARIOS

In evaluating alternative waste management scenarios, it becomes apparent that each approach carries distinct environmental implications, along with their own set of benefits and drawbacks. Firstly, an increased focus on recycling presents a promising avenue for reducing the environmental footprint of MSW management. By diverting more materials away from landfills and incineration, recycling conserves resources and minimizes energy consumption and greenhouse gas emissions. However, it's important to acknowledge that the environmental benefits of recycling can vary depending on the efficiency of the recycling process, transportation, and market demand for recyclables. Ensuring high recycling rates and reducing contamination in recycling streams is vital to maximize its positive environmental impact. Waste-to-energy technologies, such as incineration with energy recovery, can be beneficial in terms of energy production and waste volume reduction. By generating electricity or heat from waste, these technologies can offset the need for fossil fuels, reducing greenhouse gas emissions. However, they do come with concerns related to air emissions and ash management, necessitating strict pollution control measures to mitigate environmental risks.

Composting is another alternative scenario with notable environmental advantages. Organic waste diversion through composting not only reduces landfill methane emissions but also produces valuable compost that can improve soil health and reduce the need for chemical fertilizers. The drawbacks, however, lie in transportation emissions and the potential for odors and nutrient runoff in poorly managed systems. Ultimately, the choice of the most suitable waste management scenario should be made by considering local conditions, available infrastructure, and the trade-offs between environmental, economic, and social factors. A combination of these scenarios tailored to specific contexts may offer the most effective approach to mitigating the environmental impact of MSW management while optimizing resource recovery and waste reduction.

8. CONCLUSION

The LCA has not only enabled a comparative evaluation of different waste management scenarios but also highlighted the potential benefits and drawbacks of each approach. Increased recycling, waste-to-energy technologies, and composting all offer unique opportunities for reducing the environmental footprint of MSW management. However, their effectiveness depends on factors such as infrastructure, local conditions, and efficient implementation. This assessment underscores the need for sustainable, integrated waste management strategies that prioritize waste reduction, resource recovery, and environmentally responsible disposal. It emphasizes the importance of adopting a system thinking approach that takes into account the entire life cycle of MSW. By doing so, we can identify environmental hotspots, minimize trade- offs, and develop policies and practices that promote environmental sustainability in waste management. Ultimately, this LCA serves as a valuable tool for guiding decision-makers, policymakers, and communities toward eco-friendlier and more efficient MSW management systems. It is clear that addressing the environmental challenges associated with MSW management is not only an environmental imperative but also a means of conserving resources, reducing energy consumption, and mitigating climate change. As we move forward, the lessons learned from this analysis should inform and shape a more environmentally responsible and sustainable approach to handling our municipal solid waste.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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