

A WARM MODEL ANALYSIS OF KHULNA CITY'S WASTE MANAGEMENT SCENARIOS

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ABSTRACT

This study analyzes solid waste management scenarios in Khulna City, Bangladesh, through the application of Waste Reduction Model (WARM). Existing research reveals that the WARM model has not been previously applied in this region. WARM helps to reduce waste generation and environmental footprint by calculating and evaluating the life cycle impact of various waste management methods. WARM quantifies the environmental benefits of alternative waste reduction strategies (such as: recycling, composting, landfilling and incineration). In the development of this model for the present study, municipal solid waste data are collected from Khulna City Corporation, which reports approximately 477.45 tons of waste generated daily. By using the WARM model, the results showed that fourteen scenarios can be made as an alternative to increase the recycling and composting activities and to reduce the landfilling activities. However, by the implementation of the WARM model, if we could increase approximately 80% of recycling activities from solid wastes then we could minimize the waste generation and reduce the environmental harm. Therefore, this research highlights the potential of WARM to apply waste management decisions in Khulna.

Keywords: WARM, Municipal solid waste, Recycling, Landfilling, Composting

INTRODUCTION

Municipal solid waste (MSW) is everyday trash or garbage generated by households, businesses, and institutions, including food scraps, packaging, paper, plastics, and yard waste. It includes biodegradable waste (such as: food, paper etc.), recyclable materials (such as: plastics, metals, glass etc.), and non-recyclables (such as: hazardous waste, e-waste etc.). Effective management of MSW involves collection, transportation, treatment, and disposal through methods like recycling, composting, incineration, or landfilling. Proper MSW management minimizes environmental pollution, conserves resources, and improves public health and urban sanitation (Berruti, 2021).

There are various types of municipal solid waste such as: Organic Waste (includes food scraps, garden waste, and other biodegradable materials), Paper (includes: newspapers, magazines, cardboard, etc.), Plastic (bottles, bags, packaging materials, and other synthetic materials) Glass (containers such as bottles and jars), Metals (includes aluminum cans, steel products, and other metal-based materials), Textiles (old clothes, fabric waste, etc.), Hazardous Waste (includes batteries, chemicals, medical waste, and other potentially harmful materials).

Various optimization models have been developed for planning and managing municipal solid waste (MSW), with scenario-based approaches being particularly effective for addressing complex systems and guiding decisions (M. Ahani, 2019). The U.S. Environmental Protection Agency (EPA) introduced the Waste Reduction Model (WARM), an optimized life cycle inventory (LCI) tool designed to compare baseline waste management strategies with alternatives (Hassan, 2019). Waste Reduction Model (WARM) is a vital tool for reducing environmental impacts, advancing waste reduction goals, and fostering sustainable urban development (Hosseini, 2023).

WARM is an important tool because it helps municipalities, organizations, and policymakers make informed decisions for sustainable waste management by quantifying environmental benefits (Abdul Mannan Zafar, 2024). Such as: estimates GHG savings from waste management strategies, supporting climate action goals, assesses the full environmental impact of materials, from production to disposal, enabling comprehensive decision-making, highlights the environmental benefits of recycling,

composting, and energy recovery over landfilling, demonstrates how waste reduction and recycling conserve energy by avoiding raw material extraction and processing, allows users to model specific waste streams and compare scenarios, ensuring tailored solutions (Pâmela de Medeiros Engelmann, 2022). Therefore, prevention and recycling play a crucial role in modern waste management as they align with sustainable development by reducing waste destined for disposal and lowering reliance on virgin resources (Pâmela de Medeiros Engelmann, 2022). Widely used by researchers globally, WARM aids in evaluating waste management options, offering valuable insights to policymakers and waste managers for informed decision-making (Hottle, 2015). But, in Bangladesh, this model has not been used yet. In Bangladesh, landfilling is the most common method for solid waste management. But this method is not feasible for environment (Qazi, 2024). Because it requires large area of land, causes bad smell and attracts vermin, requires management and maintenance, needs replacement, poses hazards to nearby communities and risks groundwater contamination and air pollution (Blasenbauer, 2024). So, Khulna, the third largest city in Bangladesh, was chosen to start working with this model. Municipal Solid Waste Management (MSWM) in Khulna, Bangladesh, is a critical urban challenge due to rapid population growth and urbanization (Mondal, 2024). Khulna, the third-largest city in Bangladesh, generates significant amounts of waste daily, including organic, inorganic, and hazardous materials. Inefficient collection, improper disposal, and limited recycling efforts lead to environmental pollution, health hazards, and sanitation issues (Rafizul, 2024). Efforts are ongoing to implement integrated approaches, focusing on waste reduction, segregation, recycling, and environmentally friendly disposal methods like composting and landfill improvement (S.M. Moniruzzaman, 2011).

This study aims:

- To analyze the types and quantities of waste generated in Khulna city.
- To evaluate waste management practices (such as: current collection, recycling and disposal systems).
- To estimate greenhouse gas (GHG) emission for different waste management scenarios.
- To compare with alternative waste management strategies for efficiency and sustainability.
- To provide actionable insights to improve waste management and reduce environmental impacts in Khulna City.

METHODOLOGY

This research includes the following steps. 1. Study area, 2. Analysis the quality of the waste in the area, 2. Defining the possible scenarios based on the existing condition, 3. Calculating the amount of carbon emissions in each proposed scenario using WARM software, 4. Result comparison and 5. Policy recommendations.

Study area

Khulna City Corporation area is 40.79 sq. km, located in between 24°45' and 24°54' north latitudes and in between 89°28' and 89°35' east longitudes. It is bounded by Dighalia upazila and Khan Jahan Ali thana on the north, Batiaghata upazila on the south, Rupsa and Dighalia upazilas on the east and Dumuria upazila on the west. Total population of Khulna city is 770498. As of the 2022 census, Khulna City Corporation had 188579 households and a population of 719,557. It is a rapidly growing city with significant economic activities, including industries, markets, and residential zones. Daily 477.45 tons waste generated in Khulna region.

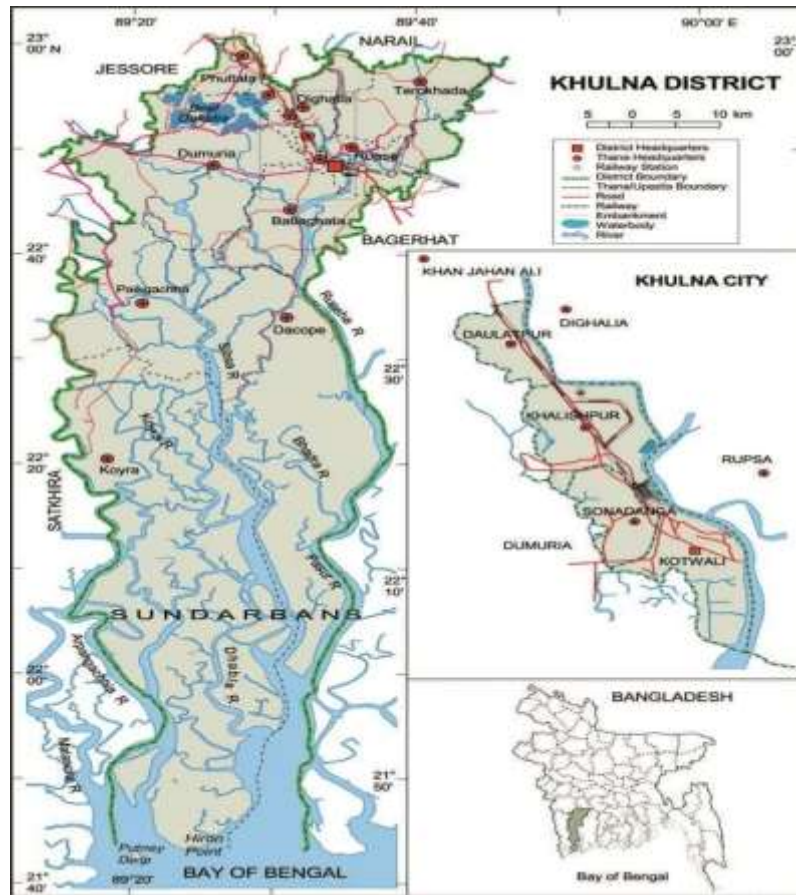


Figure 1 Location of Khulna

Khulna City manages its municipal solid waste through several landfill site, primarily overseen by the Khulna City Corporation (KCC). The key landfill site include: Rajbandh Landfill Site which is located approximately 7 kilometers from the city center, situated on the north side of the Khulna-Satkhira highway. It is easily accessible from other parts of the city, making it a strategic site for waste disposal. The Rajbandh Landfill Site is one of Khulna's primary waste dumping and disposal locations. It has been operational since 1961, making it one of the oldest waste disposal sites in the region. It covers about 20 acres area and handles approximately 315 tons of wastes per day. It accepts all types of waste and operates as an open dumping site.

This study provided a comprehensive understanding of the current waste management challenges and opportunities in Khulna City. By integrating diverse data sources and analytical tools, the research established a robust foundation for applying the WARM model and developing sustainable waste management scenarios for the city.

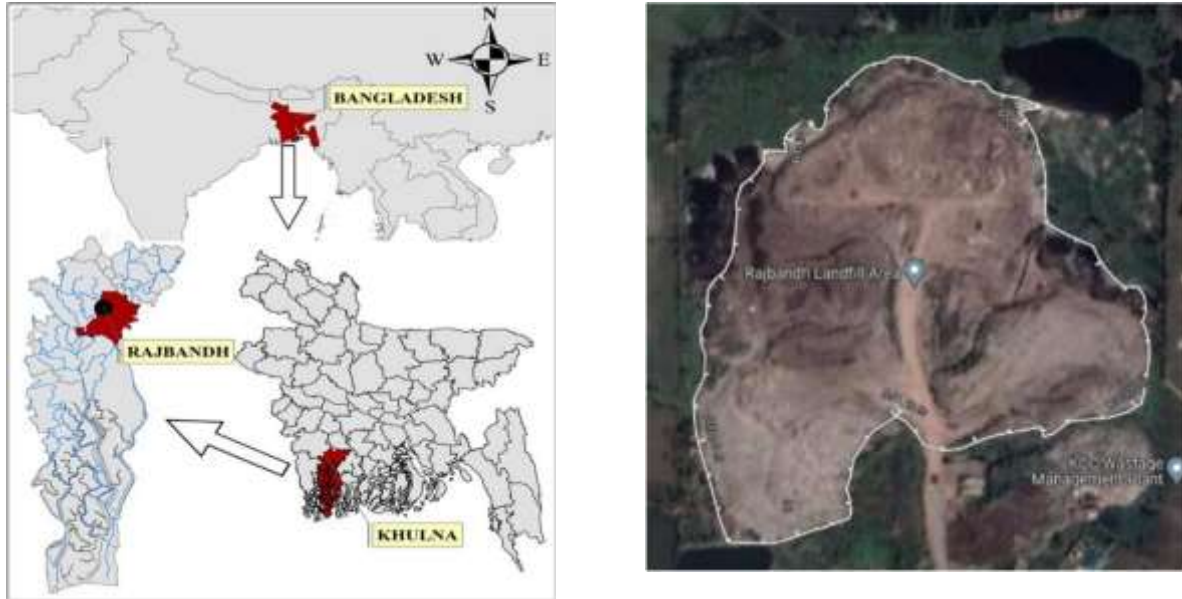


Figure 2 Rajbandh landfilling site, Khulna, Bangladesh

MSW Characterization from Khulna City

The Municipal Solid Waste (MSW) characterization of Khulna City provides a detailed understanding of the quantity and composition of waste generated within the city. On average, the city produces approximately 450-500 tons of waste daily, with a per capita waste generation rate of 0.4-0.6 kg/person/day. The waste composition primarily consists of organic waste (75-80%), followed by recyclables (10-15%) such as plastics, paper, and metals, while the remaining 5-10% comprises non-recyclable and hazardous materials which is shown in figure 3. This high proportion of organic waste indicates a strong potential for composting or anaerobic digestion as part of sustainable waste management.

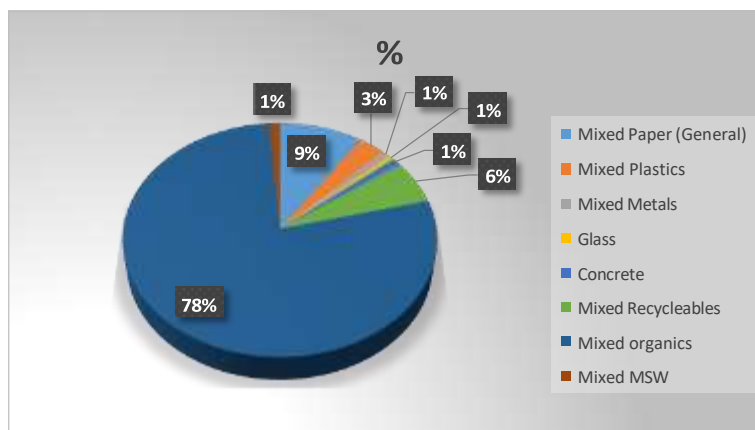


Figure 3 Amount of waste composition

The current MSW collection system faces challenges such as inadequate segregation, reliance on open dumping at the Rajbandh landfill, and limited recycling infrastructure. Seasonal variations in waste

composition, driven by festivals and agricultural activities, also add complexity. Proper waste characterization serves as the foundation for evaluating environmental impacts using tools like the WARM model, which helps analyze greenhouse gas emissions and energy recovery potentials under various waste management scenarios. These findings highlight the need for improved practices, including enhanced recycling, composting, and waste-to-energy initiatives. The following table shows the amount of generated MSW per day.

Table 1 Total MSW generated (tons/day)

Total MSW generated (tons)/day	MSW Composition	%	In tons	Recycled	Composted	Landfilled
477.45	Food and vegetables	78.0	373.18	9.05%	4.38%	86.57%
	Paper and paper products	9.5	47.5			
	Polythene and plastics	3.0	15.5			
	Textile and woods	1.3	6.51			
	Rubber and leather	1.0	2.6			
	Metal and tins	1.0	5.52			
	Glass and ceramics	0.5	2.5			
	Brick, concrete and stone	1.1	0.50			
	Dust, ash and mud products	3.7	18.24			
	Others (e.g. bone and rope)	1.2	5.40			
	Total:					

Source: (AMIMUL AHSAN, 2015)

Source: (Md. Shofiqul Islam, 2019)

WARM modeling

To determine the impact of different waste management strategies, the WARM- version 16 model is developed by EPA, was used in this study. The methodology for applying the WARM (Waste Reduction Model) to analyze Khulna City's waste management scenarios involves using detailed MSW characterization data as inputs to evaluate the greenhouse gas (GHG) emissions and energy impacts of various waste management strategies. First, the MSW data is categorized into WARM-compatible waste streams, such as food waste, paper, plastics, metals, and yard waste which was shown in above figure 3. The quantities for each category are input into the WARM model, along with current disposal methods (e.g., landfilling, open dumping, and limited recycling). The following table 2 shows the baseline approaches of applying WARM model.

Next, multiple scenarios are developed to simulate alternative waste management practices, including increased recycling, composting of organic waste, and the adoption of waste-to-energy technologies. The WARM model calculates the GHG emissions and energy use for each scenario based on lifecycle analysis principles. Results are compared across scenarios to identify the most environmentally beneficial strategies for Khulna City. This process highlights the potential for reducing emissions, recovering resources, and minimizing environmental impacts through improved waste management practices.

Table 2 Baseline approaches for applying WARM model

Material	Tons Recycled	Tons Landfilled	Tons Combusted	Tons composted	Tons Anaerobically Digested	Total Tons Generated
Mixed Paper (General)	4.5	43	0	0	0	47.5
Mixed Plastics	1.5	14	0	0	0	15.5
Mixed Metals	0.52	5	0	0	0	5.52
Glass	0.25	2.25	0	0	0	2.5
Concrete	0.05	0.45	0	0	0	0.5
Mixed Recycleables	2.59	24.76	0	0	0	27.35
Mixed organics	0	355.18	0	18	0	373.18
Mixed MSW	0	0.56	0	0	0	5.4
Total	9.41	445.2	0	18	0	477.45

Statistical Methods

The statistical methods used in in this study, are designed to systematically analyze data related to municipal solid waste (MSW) generation, composition, and the environmental impact of various waste management practices. The study begins by employing descriptive statistical methods to summarize and quantify waste data collected from field surveys and secondary sources. Key metrics such as mean, median, standard deviation, and variance are calculated to understand the central tendency and dispersion of waste generation rates across residential, commercial, and institutional sectors in Khulna City. This step helps identify patterns and variability in MSW generation across different socioeconomic and geographic zones.

To evaluate the effectiveness of different waste management strategies, the study uses comparative statistical analysis. The WARM model is applied to simulate scenarios such as business-as-usual (open dumping), enhanced recycling, composting, and waste-to-energy adoption. For each scenario, greenhouse gas (GHG) emissions are estimated, and percentage changes in emissions relative to the baseline are calculated. This allows for a clear comparison of the environmental benefits of each waste management strategy. Additionally, statistical tools such as trend analysis are used to forecast potential impacts over time, highlighting the long-term benefits of transitioning to more sustainable practices.

Furthermore, correlation and regression analysis are applied to explore relationships between waste generation rates and factors such as population density, income levels, and seasonal variations. These analyses provide insights into the key drivers of waste generation, which are crucial for designing targeted interventions. The study also incorporates sensitivity analysis to evaluate how changes in input data (e.g., waste composition percentages or management practices) impact the WARM model's outputs. This ensures the robustness of the results and helps identify critical parameters that influence GHG emissions. Overall, the statistical methods provide a comprehensive framework for evaluating and optimizing waste management scenarios in Khulna City, paving the way for evidence-based decision-making.

To ensure the reliability and robustness of the results, sensitivity analysis is performed to examine the impact of variations in input data on the model's outputs. For example, slight changes in waste composition, collection efficiency, or recycling rates are tested to evaluate how they influence GHG emissions and resource recovery outcomes. This approach helps identify critical parameters that significantly affect the model's predictions, ensuring that the results are robust and applicable to real-world decision-making. Overall, the statistical methodology combines multiple tools to provide a detailed and reliable analysis of Khulna City's waste management scenarios, supporting evidence-based policy and planning for sustainable urban waste management

The final step in the statistical methodology involves visualizing the results to support decision-making. Data from the descriptive, comparative, and sensitivity analyses are presented using charts, graphs, and tables. For instance, bar graphs might show the relative GHG emissions reductions across different scenarios, while pie charts can depict the composition of waste streams. Statistical outputs are also contextualized with cost-benefit analyses to provide actionable insights for policymakers and city planners.

The comprehensive application of statistical methods ensures a data-driven approach to waste management in Khulna City. The results not only quantify the environmental benefits of alternative scenarios but also provide a framework for prioritizing interventions. This methodological rigor makes it possible to design sustainable waste management strategies that align with both environmental and economic goals.

Result and Discussion

The analysis of Khulna City's Municipal Solid Waste (MSW) management techniques through the WARM (Waste Reduction Model) reveals significant differences in the environmental and economic impacts of various treatment methods. The study compares the baseline scenario (open dumping) with alternatives, including composting, enhanced recycling, incineration (waste-to-energy), and sanitary landfilling. These scenarios were assessed based on key performance metrics such as greenhouse gas (GHG) emissions, resource recovery potential, and overall environmental sustainability.

Comparison between MSW treatment techniques

In the baseline scenario, approximately 450-500 tons of waste per day is dumped at the Rajbandh landfill site without segregation, treatment, or resource recovery. This method results in substantial GHG emissions, predominantly from the decomposition of organic waste, which emits methane, a potent greenhouse gas. The lack of leachate treatment leads to groundwater contamination, further exacerbating environmental issues. The WARM analysis indicates that open dumping contributes to significant GHG emissions, estimated at 200,000 metric tons of CO₂ equivalent annually, making it the least sustainable option. From the baseline scenario it shows that the GHG emissions estimated at 376.97 which is shown in the figure below.

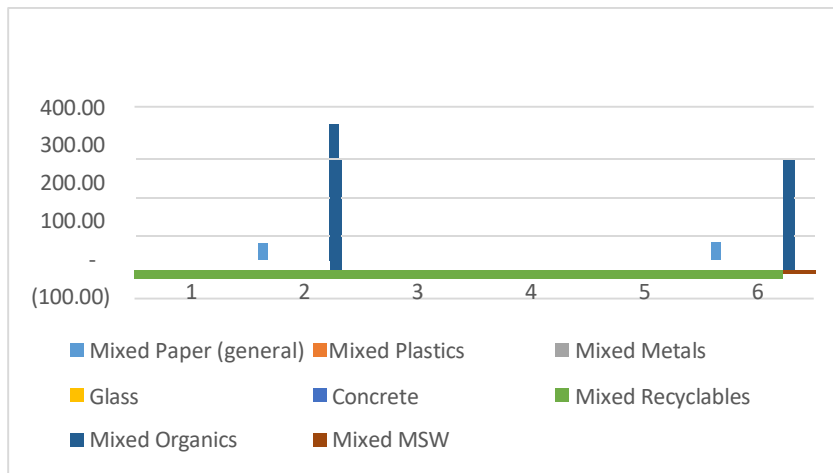
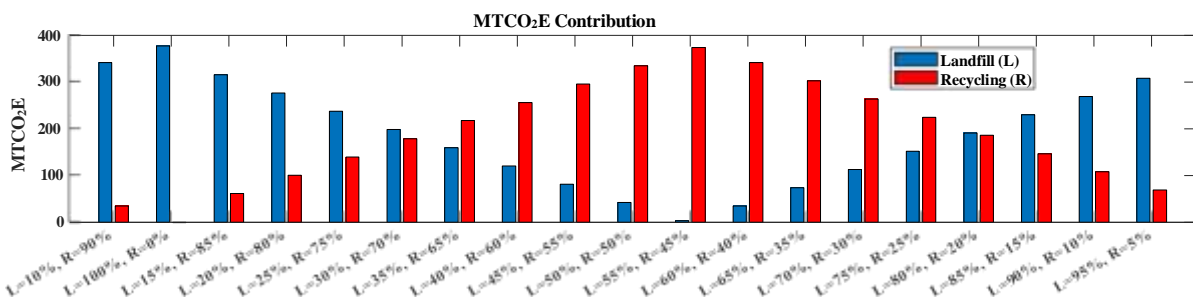


Figure 4 GHG emissions from Baseline Waste Management

Enhanced recycling focuses on recovering valuable materials such as plastics, metals, paper, and glass, which constitute about 20–25% of Khulna's waste stream. Recycling not only reduces the volume of waste requiring disposal but also significantly mitigates GHG emissions by reducing the demand for virgin material production. According to the WARM model, a robust recycling program could reduce GHG emissions by 30–40% compared to the baseline while conserving natural resources. The main challenges in implementing enhanced recycling include the lack of formalized recycling systems and market fluctuations in recyclable material prices. Informal waste pickers already contribute to recycling efforts, but their integration into a formal system with better working conditions and incentives would further enhance resource recovery. The following figures for increasing the recycling process are given below.



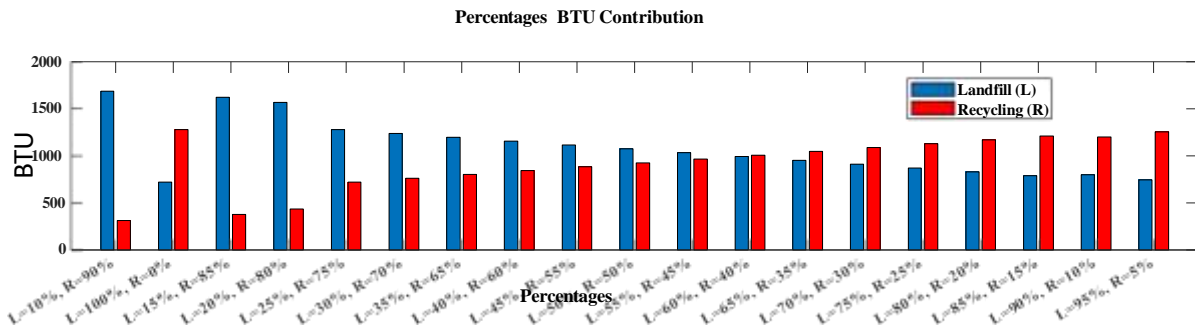


Figure 5 Landfill and Recycling comparison of MTCO₂E and BTU

Incineration, combined with waste-to-energy (WTE) technology, provides an efficient solution for non-recyclable and residual waste. The WARM analysis highlights that WTE could achieve a GHG reduction of 20–30% compared to open dumping, primarily by offsetting fossil fuel-based energy production. Incineration also significantly reduces the waste volume, requiring less space for landfilling. However, the high initial investment and operational costs associated with incinerators are major barriers for Khulna. Additionally, incineration requires a controlled waste stream with low moisture content, which can be challenging given the high organic content in the city’s waste. Proper emissions control technology is also necessary to prevent air pollution from incineration. Following figures are shown below for comparing different scenarios of different recycling rate.

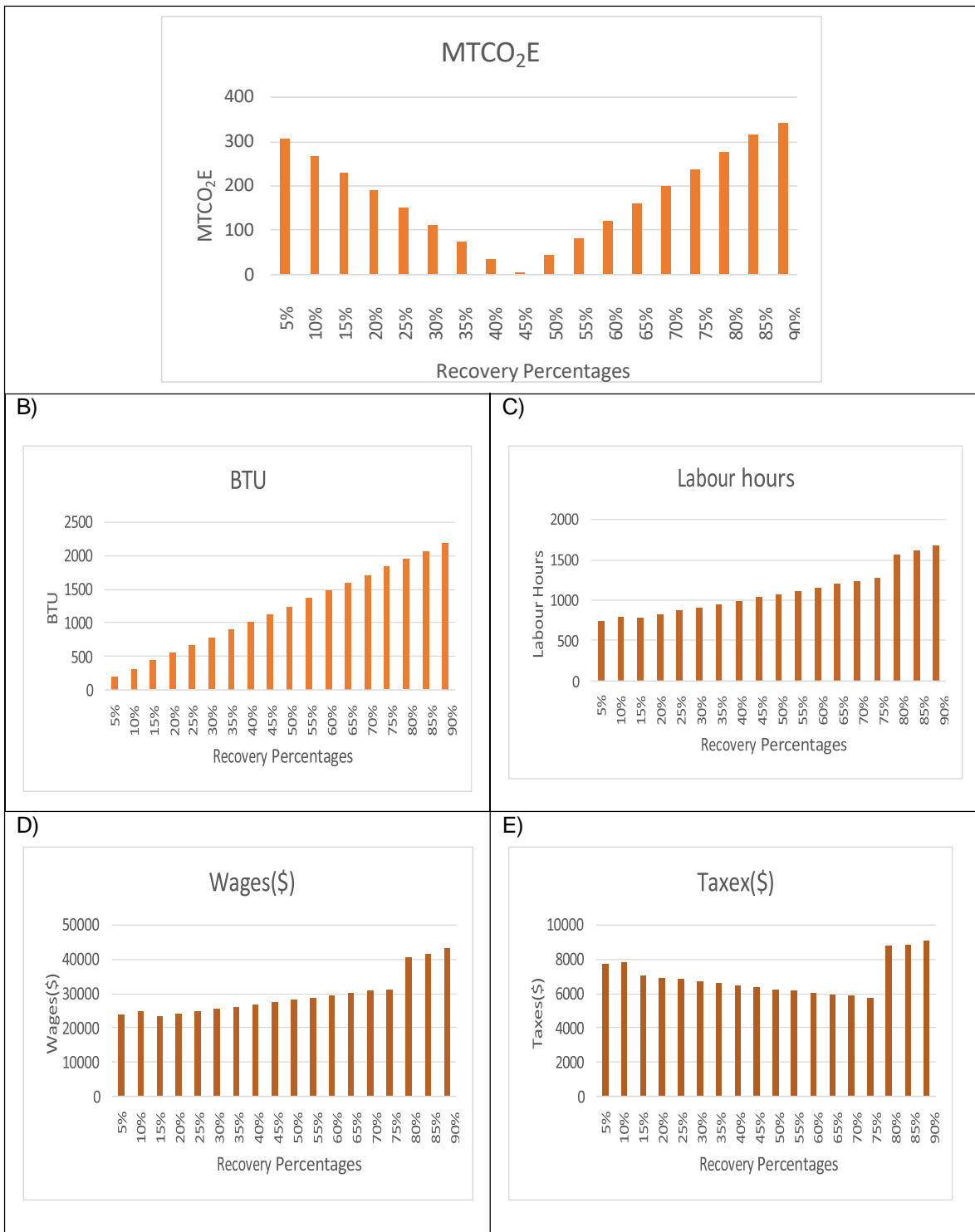


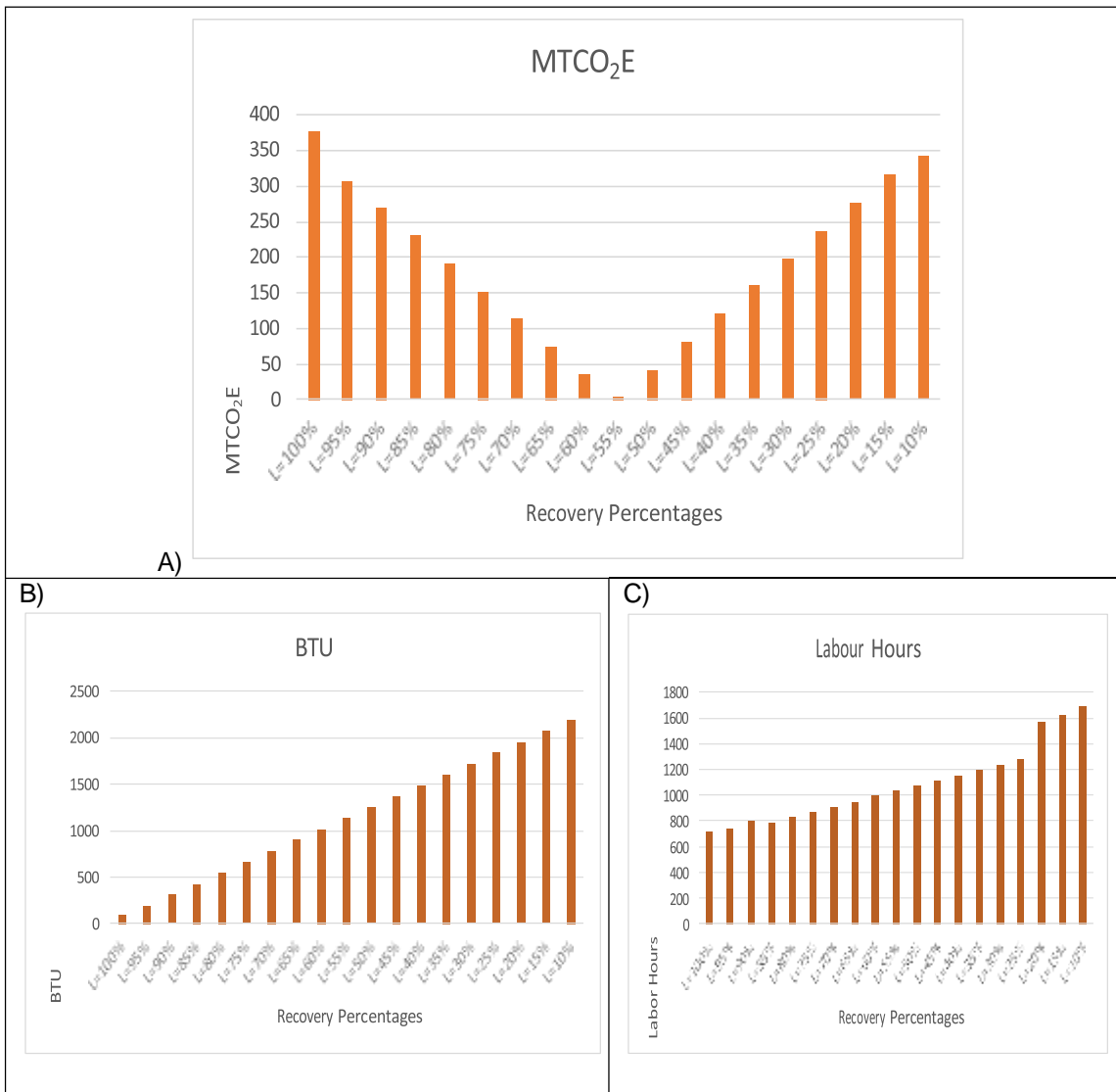
Figure 6 Comparison between scenarios with different recycling rates A) MTCO₂E, B) BTU, C) Labour Hours, D) Wages and E) Taxes

Composting diverts organic waste from landfills, thereby reducing methane emissions. The WARM model estimates that composting could reduce GHG emissions by 50–60% compared to open dumping, primarily by avoiding methane generation. Furthermore, composting produces nutrient-rich compost that can be used in agriculture, promoting soil health and reducing reliance on chemical fertilizers. However, the effectiveness of composting depends on proper segregation at the source, which is currently lacking in Khulna. Implementation would require awareness campaigns and infrastructure for

waste separation. Economically, composting is cost-effective but may face challenges in market acceptance of compost products.

Upgrading the current Rajbandh landfill to a sanitary landfill with leachate treatment and methane recovery systems offers a relatively cost-effective and practical solution. Sanitary landfills can reduce GHG emissions by 10–20% compared to open dumping, especially if methane is captured and used as an energy source. The WARM model suggests that while sanitary landfilling is less effective in reducing emissions compared to recycling or composting, it remains a viable short-term solution for Khulna. The main limitation of this approach is the finite availability of land, as the existing Rajbandh site is nearing capacity. Moreover, sanitary landfilling does not promote circular economy principles, as it lacks resource recovery compared to other methods.

Comparison between different landfilling and composting rates for different scenarios are shown in the figure below.



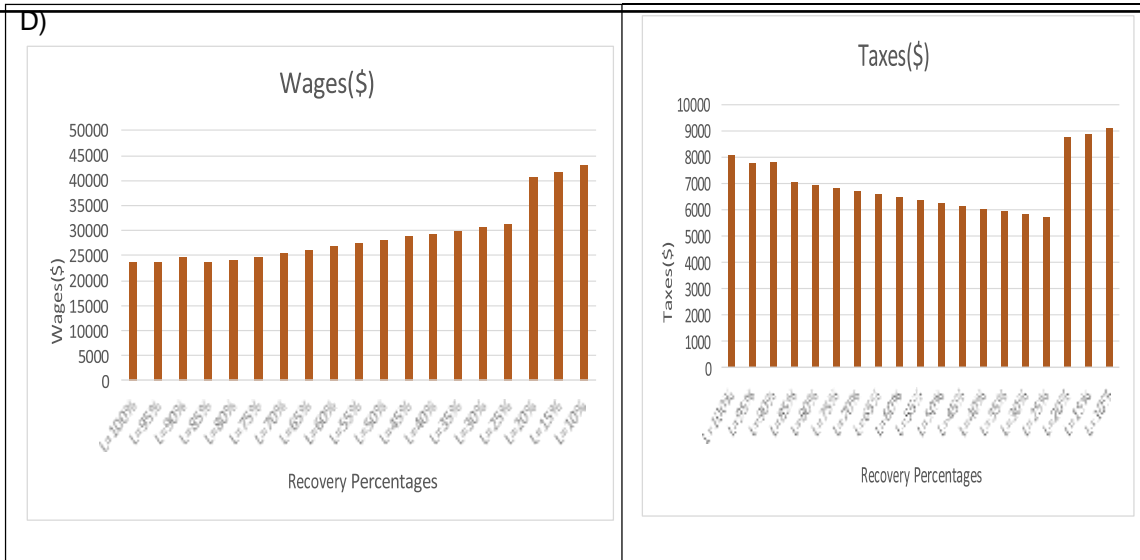


Figure 7: Comparison between scenarios with different recycling rates A) MTCO₂E, B) BTU, C) Labour Hours, D) Wages and E) Taxes

The comparative analysis of these techniques reveals that no single method is sufficient to address Khulna's waste management challenges. Composting emerges as the most effective solution for managing the city's high organic waste content, while recycling plays a critical role in recovering valuable materials and reducing environmental impacts. Incineration and sanitary landfilling serve as complementary methods for residual waste management but require significant investment and regulatory oversight. An integrated waste management system combining composting, recycling, WTE, and sanitary landfilling would yield the best results. Such a system would maximize resource recovery, minimize environmental impacts, and align with sustainable development goals (SDGs). The WARM model demonstrates that implementing a combination of these strategies could reduce GHG emissions by up to 70% compared to the baseline, contributing significantly to climate change mitigation.

The environmental benefits of adopting sustainable waste management practices extend beyond GHG reduction. Improved waste management could mitigate water and soil pollution, enhance public health, and create green jobs in sectors such as recycling and composting. Economically, resource recovery and waste-to-energy initiatives could reduce municipal waste management costs in the long term, despite high initial investments.

The results of the WARM model analysis underscore the need for a multi-pronged approach to waste management in Khulna City. While composting and recycling offer significant environmental benefits, they must be supported by investments in infrastructure, public awareness, and regulatory reforms. An integrated system leveraging the strengths of each treatment technique can transform Khulna's waste management system into a sustainable, circular model. By doing so, the city can reduce its environmental footprint and improve the quality of life for its residents.

Current situation of MSW in Khulna City and future perspectives

Khulna City generates a significant amount of municipal solid waste (MSW), primarily due to rapid urbanization and population growth. Current estimates suggest that approximately 600–650 tons of waste are generated daily, with a high organic content constituting over 70% of the waste stream. Despite these figures, the existing waste management system in Khulna struggles to cope with this volume due to inadequate infrastructure, poor collection efficiency, and a lack of public awareness. This has led to open dumping practices, particularly at the Rajbandh landfill site, which is currently overburdened and unsanitary.

The WARM (Waste Reduction Model) analysis highlights the inefficiencies in the current waste management scenario. Open dumping, which is the predominant disposal method in Khulna City, contributes significantly to greenhouse gas (GHG) emissions, particularly methane. The absence of proper waste segregation exacerbates the issue, as recyclable and compostable materials are mixed with hazardous and inert waste. The city's waste collection coverage is around 50-60%, leaving a substantial portion of waste uncollected and contributing to environmental pollution and public health risks.

The analysis also identifies challenges in waste transportation and processing. Khulna's waste collection system relies on outdated vehicles, and most waste is transported without compaction, increasing transportation costs and emissions. Additionally, the Rajbandh site lacks basic facilities like leachate collection systems and gas recovery units, leading to severe groundwater contamination and air pollution. These inefficiencies underscore the need for urgent intervention to transition towards a more sustainable waste management system.

In terms of future perspectives, the study suggests that an integrated approach to MSW management is critical for achieving sustainability. Composting presents a promising solution, as the high organic content of Khulna's waste makes it suitable for producing organic fertilizers. Implementing community-based composting programs can reduce waste volume at the source and mitigate methane emissions at the landfill. Additionally, enhanced recycling initiatives can recover valuable materials like plastics, metals, and paper, reducing the need for virgin resources.

The WARM analysis further emphasizes the potential of waste-to-energy (WTE) incineration as a viable option for Khulna City. While the capital costs for WTE plants are high, the long-term benefits include significant reductions in GHG emissions and energy generation from waste. However, the success of WTE technology depends on proper waste segregation to ensure feedstock quality and the development of robust policy frameworks to attract investment and manage operational challenges.

Sanitary landfilling is another critical component of the proposed integrated system. The study suggests that the current Rajbandh site should be upgraded to meet sanitary landfill standards, including the installation of leachate collection systems, gas recovery units, and proper liners to prevent groundwater contamination. This upgrade would ensure that only residual waste from recycling, composting, and WTE processes is sent to the landfill, significantly reducing environmental impacts.

Public participation and awareness are pivotal to the success of any future waste management strategy. The study highlights the importance of community engagement through educational campaigns, workshops, and incentive programs to encourage waste segregation at the source. Establishing neighborhood-based waste management committees can also foster a sense of ownership and responsibility among residents, leading to better compliance with waste management practices.

From a policy perspective, Khulna City needs to adopt stricter regulations and enforcement mechanisms to reduce open dumping and promote sustainable practices. The study recommends introducing Extended Producer Responsibility (EPR) frameworks to hold manufacturers accountable for the lifecycle of their products, particularly for plastic waste. Incentives for private sector participation in recycling and WTE projects can also accelerate the transition to a circular economy.

In addition to technical and policy interventions, financial sustainability is a critical aspect of future waste management in Khulna. The study proposes implementing user fees based on waste generation to finance waste collection and processing services. International funding and partnerships can also play a significant role in supporting infrastructure development and capacity building for modern waste management systems.

Overall, the WARM analysis underscores that the current situation of MSW in Khulna City is unsustainable and poses significant environmental and public health risks. However, the future holds promising opportunities if the city adopts an integrated and multi-faceted approach to waste management. By combining composting, recycling, WTE, and sanitary landfilling with strong policy support and community engagement, Khulna can pave the way for a cleaner, greener, and more sustainable urban environment.

Conclusions

The WARM (Waste Reduction Model) analysis of Khulna City's waste management scenarios highlights the urgent need for a shift from the current unsustainable practices to an integrated and sustainable waste management system. The baseline scenario of open dumping at the Rajbandh site contributes significantly to environmental degradation, with high greenhouse gas (GHG) emissions, groundwater contamination, and air pollution. Without intervention, these challenges will escalate as waste generation increases with population growth and urbanization.

Sustainable alternatives such as composting, enhanced recycling, waste-to-energy (WTE) incineration, and sanitary landfilling offer significant opportunities to reduce GHG emissions, recover resources, and mitigate environmental impacts. The WARM model demonstrates that an integrated approach combining these methods can achieve up to 70% reduction in GHG emissions, contributing to global climate change mitigation goals. Among the strategies, composting and recycling show the highest potential for environmental and economic benefits, given Khulna's high organic waste content and valuable recyclable materials.

Moving forward, implementing these solutions requires a multi-pronged effort, including public awareness campaigns, financial investment in infrastructure, and strong regulatory frameworks.

Collaboration between government, private sectors, and local communities will be critical to achieving a sustainable waste management system. By transitioning to these practices, Khulna City can significantly improve its environmental footprint, enhance public health, and create economic opportunities, positioning itself as a model for sustainable urban waste management in Bangladesh.

It is pertinent to mention that, this type of study is not frequently carried out in Khulna city, making this study an example and a potential model to be used in other cities of Bangladesh to guide decision-making.

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