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Assessment of CO_2 Emissions from Solid Waste at Kebon Kongok Landfill Using Warm Analysis

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Abstract: The impact of climate change is interrelated with greenhouse gas emissions. The pollutants from greenhouse gases come from carbon dioxide (CO_2) and methane gases. Therefore, estimating the CO_2 emission contributing to the greenhouse phenomenon's hazardous environment is crucial. The Waste Reduction Model (WARM), created by the Environmental Protection Agency (EPA), provides high-level comparisons of potential greenhouse gas emissions reductions, energy savings, and economic impacts when considering different materials management practices. Materials management practices in WARM include source reduction, recycling, anaerobic digestion, combustion, composting, and landfilling. It can be noted that most landfill sites do not have materials recovery facilities for recycling purposes. Thus, it is crucial to estimate the potential impact of recycling efforts, as this could lead to a significant reduction in the amount of garbage going to landfills and limit CO_2 emissions. This study examines the environmental and economic impacts of solid waste management practices at the Kebon Kongok Landfill in West Lombok, Indonesia, and the potential of adopting recycling activities. WARM can estimate greenhouse gas (GHG) emissions, energy consumption, and potential revenue from recycling activities in these two regions (Mataram and West Lombok). Raw data from the daily waste collection in the landfill from both sites were collected, and the amount was inserted into WARM. The results demonstrate the efficacy of recycling scenarios in reducing GHG emissions and conserving energy. It can be noted that Mataram's recycling efforts can result in a value of 1,149.45 $MTCO_2E$ reduction, which is more than double the 450.81 $MTCO_2E$ in West Lombok. Hence, the energy saving of 8183.95 MBTU for Mataram can be significantly achieved compared to West Lombok (3159.87 MBTU). The research highlights the economic benefits of recycling for both regions if the recycling effort is adopted on-site. In Mataram, recycling activities can yield a substantial revenue of USD 45.6494 from mixed paper alone. Meanwhile, mixed paper recycling in West Lombok can generate a significant income of USD 18.0139. These findings underscore the effectiveness of recycling initiatives in reducing GHG emissions, conserving energy, and generating economic value while emphasising the importance of tailored waste management strategies to address regional variations in waste composition and consumption patterns. Therefore, strong policymaking can be introduced to adapt recycling activities for income generation, thereby transforming waste into wealth in achieving a circular economy.

Keywords: Solid waste management, greenhouse gas emissions, recycling activities, energy consumption, waste reduction model.

1. Introduction

Population expansion and an increase in urbanisation have contributed to the excessive volume of waste generated. Moreover, improper solid waste management has emerged as a critical issue that will pose significant health risks related to environmental pollution for the inhabitants (Tesseme et al., 2022; Velis & Cook, 2021; Vinti et al., 2021). In addition, with its vast territory and high population, Indonesia has grappled with a substantial amount of solid waste production, particularly in urban areas (Abir et al., 2023). The demographic data suggests that municipal solid waste in Indonesia has steadily risen, exacerbated by rapid urbanisation and population growth (Brotosusilo & Handayani, 2020; Gunawan et al., 2020). This surge of waste production strains existing waste management infrastructure and exacerbates environmental pollution, which later contributes to significant greenhouse gas (GHG) emissions. Therefore, effective waste management strategies must be implemented to mitigate the adverse impacts of municipal solid waste generation.

Greenhouse gas emissions from the waste sector, predominantly from landfill disposal, pose significant environmental concerns, including climate change and pollution (Chen et al., 2020; de Meij, 2020). The waste sector accounts for a substantial portion of national GHG emissions in Indonesia, underscoring the urgency for effective waste management interventions to mitigate climate impacts (MEF, 2021).

In response to global climate commitments, including the Paris Agreement, Indonesia has set ambitious targets to reduce GHG emissions. This necessitates proactive measures to improve waste management practices. However, addressing municipal solid waste (MSW) challenges requires more than just ambition. It demands localised solutions tailored to specific regions, considering unique socio-economic and environmental contexts.

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NTB Province in Indonesia is one of the regions facing a pressing waste management issue. The province is contending with mounting waste generation, which is impairing environmental degradation and posing challenges to tourism development, a vital economic sector (Hardesty et al., 2016; Landrigan et al., 2020; Dabrowska et al., 2021). The situation at the Kebon Kongok landfill, a prominent waste disposal site in NTB Province, underscores the urgency of improving waste management practices and mitigating environmental impacts.

While previous studies have explored various aspects of waste management in the Kebon Kongok landfill, there is still a gap in understanding the comprehensive GHG emissions associated with different waste management scenarios. This study aims to fill this gap by quantifying GHG emissions from MSW management in the Kebon Kongok landfill using a waste reduction model (WARM). The use of WARM analysis as a free web tool provided by the Environmental Protection Agency (EPA), United States, is to aid solid waste planners and organisations in tracking and voluntarily reporting on greenhouse gas (GHG) emissions reductions, energy savings, and economic impacts from several different waste management practices (EPA, 2018). Therefore, the potential impact of adopting recycling activities in the regions, following the results estimated by WARM in transforming waste into wealth and achieving a circular economy, is significant in reducing GHG. Moreover, this research seeks to inform evidence-based decision-making and long-term planning for sustainable waste management in NTB Province by evaluating GHG emissions and energy savings. This study's significant contribution to the broader discourse on MSW management in Indonesia underscores the importance and impact of the research. Overall, this study is expected to significantly contribute to the broader discourse on MSW management in Indonesia and offer valuable insights into mitigating GHG emissions and promoting environmental sustainability in the region.

2. Research methodology

The case study was conducted at the Kebon Kongok landfill in West Lombok Regency, Indonesia. The landfill, which covers 8.6 hectares, has been operating since 2006. Data for this study were sourced from the landfill's Regional Technical Implementation Unit and the Department of Environment and Forestry Service of NTB Province, demonstrating a collaborative effort with local authorities to ensure the credibility of the study. The raw MSW data from the Kebon Kongok Landfill has been collected for one week, from 1st August to 8th August 2023. This data calculates recycling activities using a ratio percentage (EPA, 2018). Figure 1 depicts the flowchart outlining the municipal solid waste (MSW) data analysis process conducted for this research. This flowchart illustrates the steps for analysing MSW data collected from the Kebon Kongok landfill. The data obtained from the landfill was processed to determine weight and total amounts, referencing

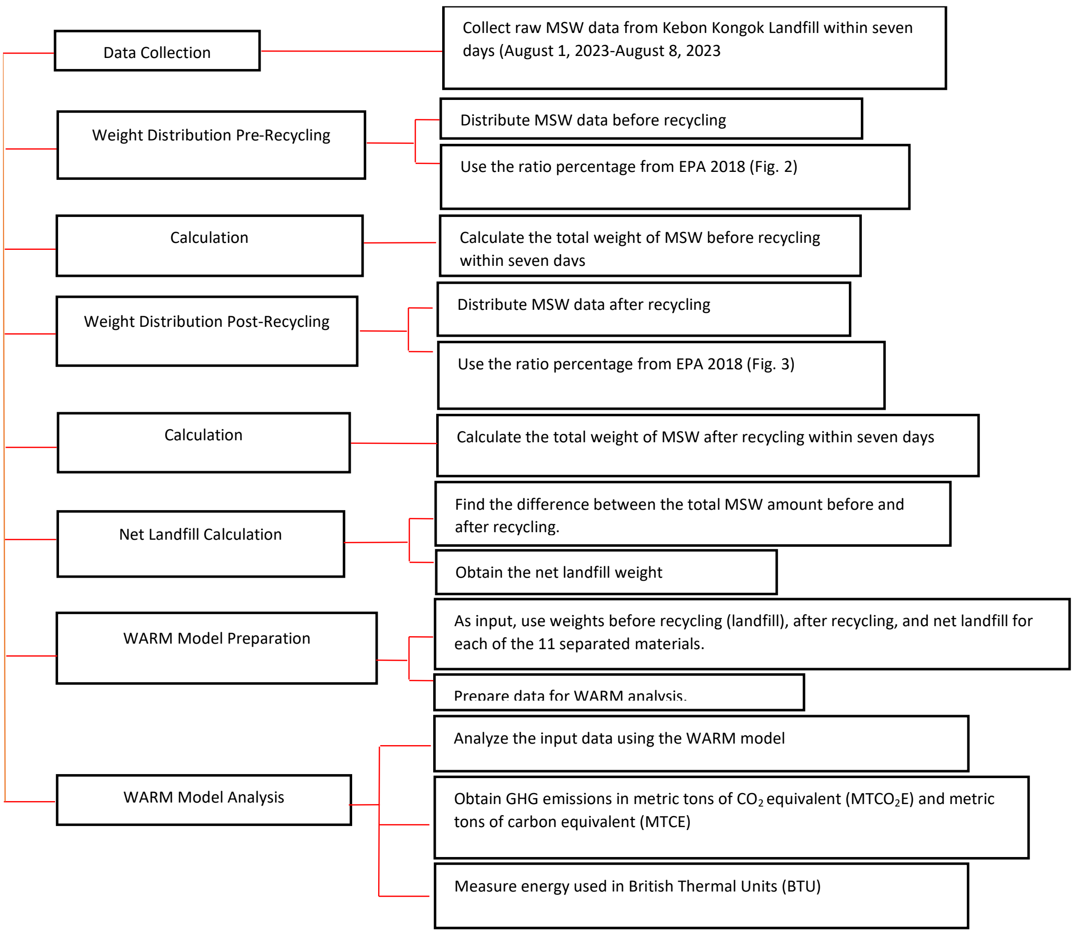

Figure 1. Municipal Solid Waste Data Analysis Flowchart

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Figure 2 and Figure 3. Subsequently, the results obtained were assessed using WARM analysis to calculate GHG emissions and energy savings regarding carbon dioxide equivalents ($MTCO_2E$) and metric tonnes of coal equivalents (MTCE).

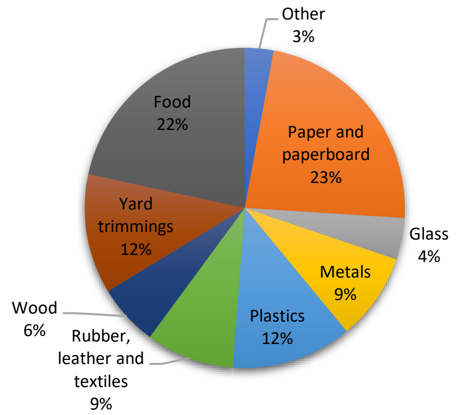

Figure 2. Total MSW generation 292.4 million tons (before recycling by material) (EPA, 2018)

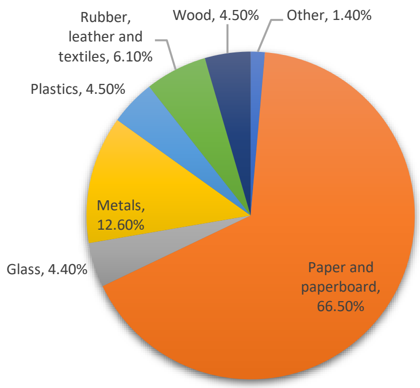

Figure 3. Total MSW recovery (69.1 million tons by material) (EPA, 2018)

2.1 Waste Reduction Model (WARM)

From the input of the weight distribution in pre-recycling and post-recycling (see Figure 1), the later steps are to assess the net landfill weight to estimate GHG emissions using the highly significant WARM model. The data analysis compared the baseline landfill scenario with alternative scenarios involving recycling, waste composition, and tonnage reduction. The WARM model, a crucial tool in the field, facilitated the calculation of GHG emissions across various material types commonly found in MSW. Key outputs from the model include:

a) Metric tonnes of carbon dioxide equivalent ($MTCO_2E$)

b) Metric tonnes of carbon equivalent (MTCE)

c) Energy units measured in million British thermal units (MBTU)

The study utilised WARM, developed by the United States Environmental Protection Agency (EPA), to assess GHG emissions associated with MSW management practices. WARM facilitated simulations of various waste management scenarios, allowing for comparisons between baseline strategies and alternative methods (EPA, 2018). The software was programmed to analyse data related to waste management practices, encompassing both GHG emissions and socio-economic factors, to evaluate the overall impact of different scenarios on global warming and socio-economic conditions. Engelmann et al. (2022) reported utilising WARM to assess a broader and more accurate range of waste management options, later enabling the analysis of alternative scenarios to identify the best solutions for sustainable MSW management, offering hope for a greener future.

2.2 WARM in this case study

In this analysis, recycling assumes that recycled materials substitute virgin inputs in manufacturing processes, with constant demand for new and recycled materials. Thus, increased recycling does not alter the overall production of materials. According to WARM, each tonne of recycled material displaces virgin material that would otherwise have been produced. The WARM analysis, a significant and impactful tool, simplifies the relationship between recycling and demand for products with recycled content by assuming no change in overall demand due to increased recycling (EPA, 2020). Therefore, in the context of Indonesian waste management conditions, the WARM analysis can significantly estimate greenhouse emissions by adopting an alternative scenario, such as recycling practices for the chosen site of study, in this case, the Kebon Kongok landfill.

2.3 Greenhouse gas emissions (GHG) and energy saving in WARM

GHG savings are determined by comparing emissions from an alternative scenario with those from a baseline scenario. The emissions of the baseline scenario cannot be easily calculated by multiplying quantity with an emission factor (EPA, 2018). It is crucial to have two scenarios for an effective application of WARM energy factors: one representing current management practices (baseline scenario) and another representing alternative practices. Analysing these scenarios allows for the calculation of energy consumption or avoidance in both cases. The difference between the alternative and baseline scenarios reveals the energy consumed or avoided due to the alternative management approach (EPA, 2018).

2.4 Income generated from recyclable materials

The income generated from recyclable materials was calculated based on their weight post-recovery, which was obtained from a comprehensive and accurate representation of the total weight of municipal solid waste (MSW) collected over a seven-day period. This data was used in conjunction with the ratios provided in the MSW Fact and Figure 2018 report (EPA, 2018) (Figures 2 & 3). The weight of each material was determined by multiplying the separation percentage ratio by the total recovery weight, as outlined in the MSW Fact and Figure Recovery guidelines (EPA, 2018). Revenue from recyclable materials was then calculated by multiplying each material's

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Table 1. Market Price of Recyclable Generated (Rakhman et al., 2022)

Recyclable Items	Market Price (USD/Kg)
Glass	0.032
Mixed Paper	0.19
Mixed Metal	0.39
Mixed Plastic	0.16
Tyres	0.0054
Mixed Recyclable	NA

Note: NA- Not Available

composition by its respective market price (Rakhman et al., 2022). (Table 1). Table 1 comprises the net value of the price of recyclable materials, referring to the current market price in Indonesia (Rakhman et al., 2022).

3. Results and discussion

Figure 4 illustrates the total incremental GHG emissions in the form of carbon dioxide equivalents ($MTCO_2E$) for both Mataram and West Lombok, showcasing the source-segregated materials recycling developed in this research. Analysis of Figure 4 reveals the promising potential of recycling in reducing GHG emissions, as a positive net value indicates $MTCO_2E$ emissions savings. The results indicate nine materials with net $MTCO_2E$ savings from the recycled materials analysis. However, one non-recyclable material, yard trimmings destined for composting, exhibited negative values for incremental GHG emissions.

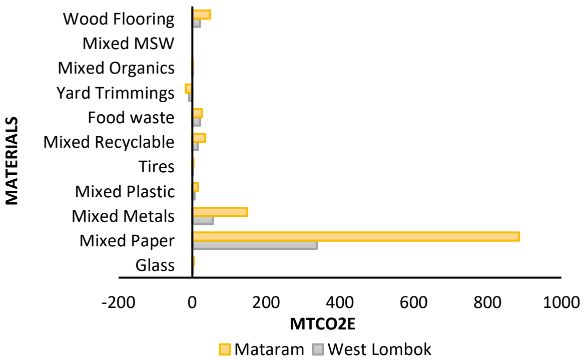

Figure 4. Total incremental $MTCO_2E$ emission

The extent of GHG savings varied significantly among Mataram's different materials. Mix paper exhibited the highest savings in total incremental GHG emissions for $MTCO_2E$ (Figure 4), with 885.46 $MTCO_2E$ for Mataram and 337.58 $MTCO_2E$ for West Lombok. Conversely, yard trimmings showed the highest incremental GHG emissions, with 18.03 MT for Mataram and 8.84 MT for West Lombok. The carbon emission results per tonne produced, depicted in Figure 5, revealed that mixed paper resulted in the highest GHG emissions savings in MTCE, with 233.31 MTCE for Mataram. Yard trimmings for Mataram recorded the highest incremental GHG emissions at 4.92 MTCE, compared to 2.41 MTCE for West Lombok. These emission variations underscore the potential impact of source reduction and recycling practices on the net GHG emissions of the materials produced, emphasising the urgency of our role in waste management.

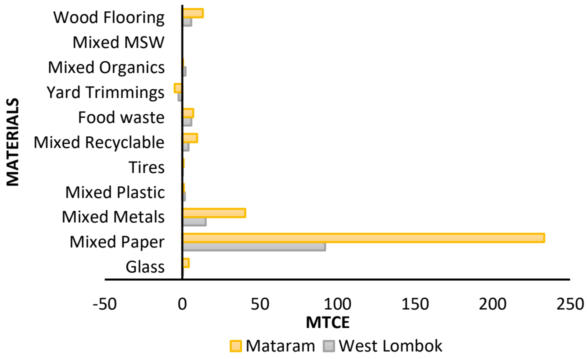

Figure 5. Total incremental of MTCE emission

The energy usage from both the baseline and alternative scenarios was assessed using the Waste Reduction Model (WARM), a widely accepted tool for evaluating the environmental impact of waste management options. Results from Mataram indicated the highest incremental energy savings, particularly from mixed paper, totalling 4903.55 MBTU. However, the maximum energy consumption was observed in the yard trimming material, with a value of 14.07 MBTU, as depicted in Figure 6. Yard trimmings were identified as contributors to increased energy consumption due to the decomposition of organic materials, which generate methane gas (CH_4). It is crucial to recognise that the atmospheric warming potential of CH_4 is 28–36 times that of CO_2 when averaged over 100 years (Chai et al., 2016). However, the recycling materials depend on the solid waste generated in both regions, and uncertainties regarding the value will later make a difference in the outcomes of the WARM analysis.

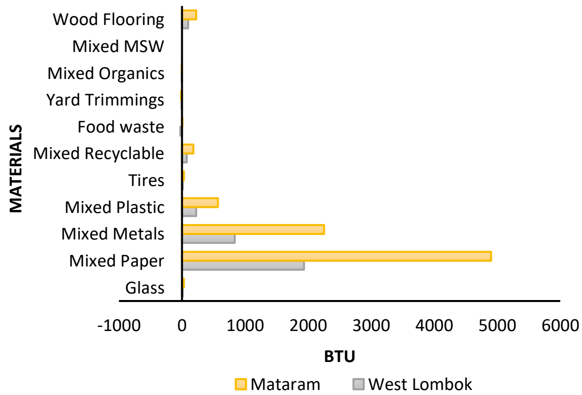

Figure 6. Total incremental energy consumption

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Figure 7 illustrates the total incremental GHG emissions of $MTCO_2E$ for Mataram and West Lombok over seven days (1 week). Core recyclables, including glass, mixed paper, metals, plastics, tyres, and others, significantly reduced GHG emissions in both Mataram and West Lombok. In Mataram, core recyclables saved 1,091.37 tonnes of $MTCO_2E$, while West Lombok saved 416.29 $MTCO_2E$. Although other materials like food waste, yard trimmings, and wood flooring also showed reductions, their impact was smaller. Mataram saved 58.08 $MTCO_2E$, and West Lombok saved 34.52 $MTCO_2E$ by recycling these materials. Overall, Mataram achieved a total GHG emission reduction of 1,149.45 $MTCO_2E$, compared to 450.81 $MTCO_2E$ in West Lombok. It highlights the potential of recycling initiatives to impact carbon emissions substantially.

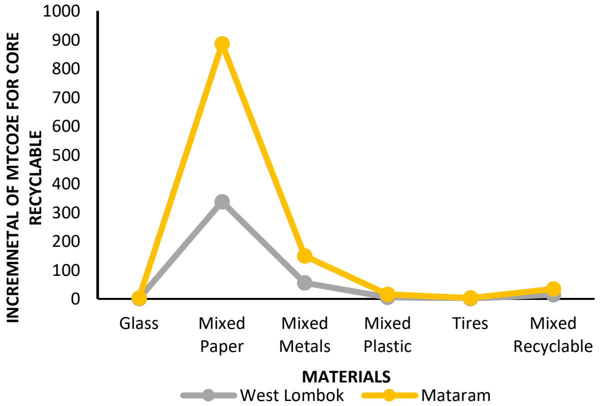

Figure 7. Total incremental of $MTCO_2E$ emission for core recyclable

The core recyclable material for MTCE emission yielded the same result (Figure 8), with the maximum saving recorded by Mataram at 289.47 MT, generating 322.53 tonnes of recycled solid waste. Like core recyclables, other materials also showed noteworthy reductions, contributing to 3096.51 MBTU in West Lombok and 7968.59 MBTU in Mataram (Figure 9). Mataram obtained the greatest total energy saving for core recyclable materials. At the same time, other materials also exhibited smaller reductions, resulting in a decrease of 63.36 MBTU in West Lombok and 215.36 MBTU in Mataram. Furthermore, the maximum energy saving was from Mataram at 8183.95 MBTU for 509.5 tonnes of total weight compared to West Lombok's 3159.87 MBTU for 232.55 tonnes.

In the context of energy-saving consumption, it is noteworthy that mixed paper exhibited a considerably more substantial value in terms of energy savings compared to GHG emissions. This discrepancy can be attributed to variations in a pivotal parameter known as the value factor. The energy factor was measured at 20.56, while the emission factor stood at 3.55 (EPA, 2023). Moreover, the GHG emissions for cardboard and office paper are lower than energy usage ratings in WARM due to its assumption of forest carbon credits for recycling paper. Forest carbon credits are a form of tradeable carbon offset that represent the avoidance of carbon emissions from deforestation or degradation of forests. Recycling reduces tree harvesting, increasing carbon

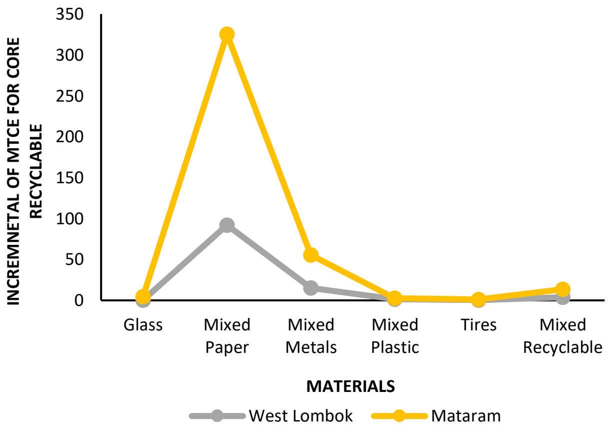

Figure 8. Total incremental MTCE emission for core recyclable

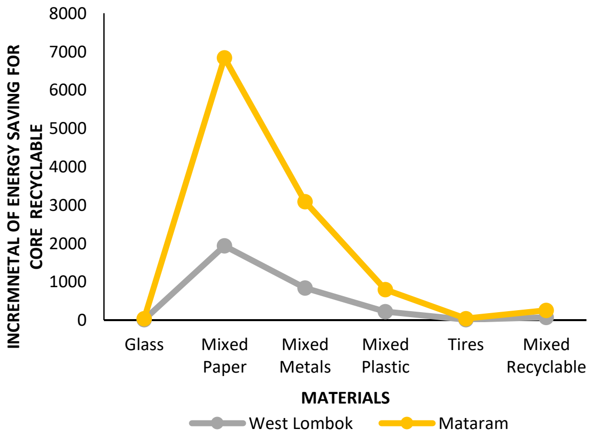

Figure 9. Total incremental energy used for recyclable core

storage in soil. Other models do not include these credits (Anshassi & Townsend, 2021).

The reduction in energy consumption achieved through recycling plays a pivotal role in minimising the environmental footprint and concurrently reducing the emission of harmful pollutants. Furthermore, saving energy from recycling not only lessens dependence on fossil fuels but also leads to significant cost savings, underlining the economic benefits of sustainable practices (Mallick et al., 2023).

GHG release is closely tied to community waste generation volume. This finding is supported by a study conducted by Abu Hassan et al. (2019). Their research established that increased waste production correlates with higher greenhouse gas emissions. Consequently, actively decreasing GHG emissions becomes imperative to mitigate environmental impact, reduce pollutants, and enhance control, ultimately prioritising the well-being and health of the local population (Abu Hassan et al., 2019). Moreover, to reduce GHG emissions, there is technology in landfills for gas capture for methane gases as a mitigation strategy

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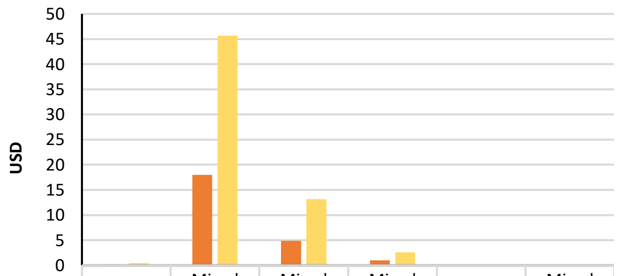
for limiting GHG emissions. Therefore, lifecycle-based environmental assessment can be conducted to mitigate landfill gas emissions. Environmental professionals, policymakers, and stakeholders play a crucial role in implementing these measures, such as cover and gas collection, along with energy utilisation at ageing landfills. This will lead to significant environmental improvements compared to the baseline scenario with no emission mitigation action (Scheutz et al., 2023).

The estimation of revenue from recyclables, as presented in Figure 10, sheds light on the potential economic benefits of recycling initiatives in West Lombok and Mataram. In West Lombok, recyclable items include glass, mixed paper, mixed metal, mixed plastic, tyres, and mixed recyclables. The market prices per kilogram and their respective amounts in tonnes contribute to the estimated revenue. Notably, the high market price of mixed metal at USD 0.39 per kilogram results in a substantial value of USD 4.8828 for the 12.52 tonnes recycled, indicating a lucrative avenue for generating revenue. Similarly, mixed paper, with a significant amount of 94.81 tonnes and a market price of USD 0.19 per kilogram, contributes substantially to the total revenue, amounting to USD 18.0139.



	Glass	Mixed Paper	Mixed Metal	Mixed Plastic	Tires	Mixed Recyclable
West Lombok	0.1651	18.0139	4.8828	1.0192	0.0167	0
Mataram	0.3994	45.6494	13.1586	2.584	0.042	0

Figure 10. Comparison of total estimation for recycling

In Mataram, a similar analysis reveals the significant economic potential of recycling. With a market price of USD 0.032 per kilogram and 12.48 tonnes, glass contributes USD 0.3994 to the estimated revenue. The most significant contributor, mixed paper, with 240.26 tonnes and a market price of USD 0.19 per kilogram, generates a substantial value of USD 45.6494. These findings, corroborated by research in the field, such as the work of Larouche et al. (2020), underscore the economic benefits of recycling programmes. They demonstrate how strategic emphasis on high-value recyclables can significantly contribute to overall revenue, providing a promising outlook for sustainable waste management (Larouche et al., 2020).

These correlations underscore the crucial role of tailored recycling strategies that leverage market dynamics and emphasise economically valuable recyclable materials. As Ismail et al. (2018) point out, the potential revenue generated from recycling three key materials, aluminium, plastic, and paper, amounts to RM 42.50 within a short timeframe. This underscores the belief that instituting waste separation at the source not only contributes to environmental conservation but also provides a viable avenue for generating additional income for the institution. This knowledge empowers us to make informed decisions about waste management, enhancing our ability to protect the environment and our financial interests (Ismail et al., 2018).

The findings from this study of mixed paper recycling align with the findings from Samadikun et al. (2021), which specifically underscore the stable economic potential of paper waste recycling within the informal recycler sector in Purwodadi Sub-District (Samadikun et al., 2021). This stability is a reassuring factor in the volatile world of waste economics. Another study highlighted the importance of plastic recycling for Banda Aceh's economic growth. However, metals, once valuable, are becoming scarcer due to advancements in material engineering, leading to price fluctuations. In contrast, paper waste retains stable demand and price due to its consistent supply and demand pattern (Nizar et al., 2019). These implications underscore the need for further extensive consideration and detailed analysis of metal and plastic waste values in Indonesia, particularly in regions like Mataram and West Lombok, where significant revenue generation potential is observed in metals and paper, respectively.

In a different country, such as Nepal, it is suggested that the recovery of plastic materials can generate revenue, amounting to 1.38 times the cost of managing plastic waste. This potential for increased revenue is a reason for optimism in the field of waste management. It becomes achievable when the collection efficiency reaches 66.7%. Additionally, a mere 1% increase in the recovery rate and collection efficiency could cover an additional 4.64% and 2.06% of the costs of managing plastic waste, respectively (Nepal et al., 2020). However, a study conducted by Vogt et al. (2021) reported that the effective collection of used plastic waste for recycling is probably reliant on financial motivations and regulatory measures established by the government (Vogt et al., 2021). Businesses need to broaden the role of producers and encourage residents to participate actively in recycling efforts (Liu et al., 2020).

In a study by Rangga et al. (2022), it is evident that certain regions like Johor, Kedah, and Pahang in Malaysia have gained substantial profits from the sale of specific types of waste, such as plastic, paper, metal, glass, and aluminium (Rangga et al., 2022). In the United States, aluminium and plastic are reported to be major contributors to the economy after 'e-waste' recycling (EPA, 2020). 'E-waste' refers to electronic waste, such as old computers, mobile phones, and other electronic devices. Additionally, a study by Han et al. (2021) highlighted the profit potential of recycling e-waste in Japan and Korea (Han et al., 2021). Nevertheless, it is crucial to consider the costs associated with the recycling method. Genc et al. (2019) reported that the overall cost of plastic recycling through mechanical means becomes economically viable only when there is an improvement in the recovery of plastics (Genc et al., 2019). Thus, it is important to note that the profits from recycling activities can vary depending on the market price of the materials in each region and the recycling method.

It can be denoted that through proper collection of municipal solid waste, valuable sources of recycling materials such as metal can be recovered and used in new products. The latter will significantly lower the production cost and, more importantly,

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reduce the environmental impact (Larouche et al., 2020). Moreover, material recovery facilities can be included in the landfill, as the operational costs of waste management can be diminished due to the reduction of waste materials that end up in the landfill. From the results analysis, the concept of optimal waste transformation into wealth is gaining popularity, and even though fluctuations in market prices for recyclables could affect economic feasibility, the future of waste management looks promising with the increasing demand for recyclable materials, as these valuable resources and products exist in waste streams, focusing mainly on their monetary value (Kalkanis et al. 2022).

4. Conclusion

This research was conducted to comprehensively evaluate CO_2 emissions and energy consumption associated with solid waste management practices at the Kebon Kongok Landfill in West Lombok, Indonesia. By leveraging WARM, the research investigated the environmental impact of waste management strategies and compared waste segregation methods between Mataram and West Lombok. The study discovered key insights regarding the composition and generation of MSW at the landfill. The high organic content was a notable finding, with food waste and yard trimmings particularly prominent. By applying the WARM analysis, the study demonstrated the efficacy of the recycling scenario, especially for core recyclables such as mixed paper, plastics, and metals, in reducing GHG emissions and conserving energy. It aligns with the overarching goals of sustainability. By estimating the revenue that could be generated from recyclable materials, the research underscored the potential economic benefits of recycling programmes, which can contribute significantly to overall revenue and foster a circular economy. Moreover, the study revealed distinct waste generation patterns between West Lombok and Mataram, indicating the effect of regional variations in consumption patterns and waste management practices. The research emphasised the critical role of community engagement and behavioural changes in waste reduction and initial collection. These factors are essential to improving recycling rates and minimising environmental impact. Thus, the results of the evaluation of effective recycling strategies can influence policymakers to revise regulations or provide incentives for recycling programmes, which can guide industries, businesses, and citizens toward sustainable waste management practices.

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