Evaluating Sustainable Municipal Solid Waste Management Scenarios for Ulaanbaatar, Mongolia: An Integrated Life Cycle Assessment and Geospatial Analysis

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Abstract. Mongolia is facing increasing environmental threats related to waste management, including insufficient waste collection, limited treatment, and improper disposal. Over the years, the country has seen a dramatic rise in waste generation, posing a serious environmental threat. This study aims to develop a strategic framework to support decision-making in Ulaanbaatar, by promoting sustainable waste management through enhanced material recovery and recycling processes. The methodology employed in this study integrates life cycle assessment (LCA) with geospatial analysis using ArcGIS to construct and evaluate sustainable municipal solid waste management scenarios in the six central districts of Ulaanbaatar. LCA evaluates different scenarios and compares them in specific environmental contexts, including final solid waste, air, and water emissions. On the other hand, geospatial analysis is applied to identify the most suitable areas for different treatment facilities based on LCA results. According to the results of LCA, sanitary landfill will improve the current situation by lowering the global warming potential (GWP) and biological oxygen demand (BOD). Among all the proposed scenarios, Scenario 4 offered the best balance, achieving final total waste of 757,529 tons, a net reduction of greenhouse gases of 77,350 tons, and moderate BOD of 72 tons. Using Analytical Hierarchy Process (AHP) and restriction modelling, the GIS analysis identified suitable areas for three facilities, including materials recovery facility (MRF), refuse-derived fuel (RDF), and composting facilities. Overall, this study presents an integrated framework for sustainable waste management with minimal environmental impact. The study identifies the optimal treatment facilities based on scenario analysis and provides recommendations for decision-makers to improve waste management practices in Ulaanbaatar city.

Keywords: Municipal solid waste, Life cycle assessment, Geographic information system.

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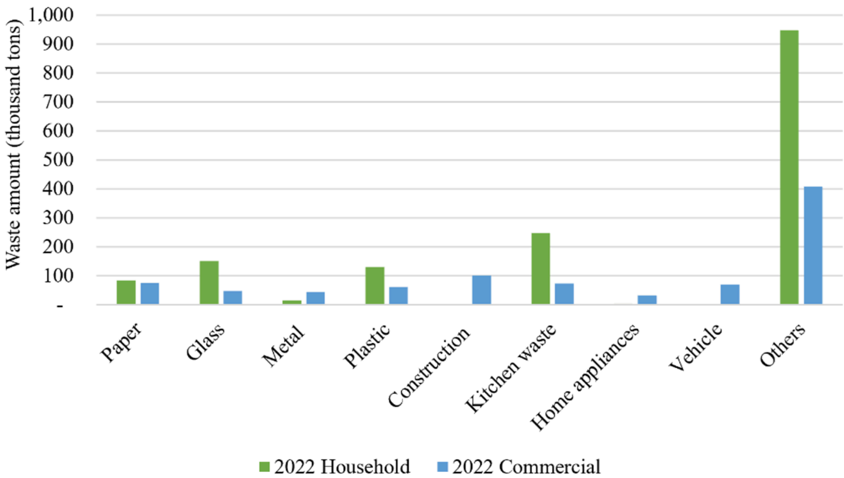
1 Introduction

Ulaanbaatar is the capital city of Mongolia and home to 49.5% of the total population as of 2023 (1,734,848 out of 3,504,741) [1]. Between 2021 to 2022, the amount of waste generation increased from 2402.5 thousand tons to 2496.5 thousand tons, a total increase of 3.9%. In the same year, the total rise of hazardous waste was 28.2%, from 223.0 thousand tons to 285.9 thousand tons. As for waste characterization, 12% of the total waste is food waste, 8% of glass and plastic, 6% of paper, 4% of construction waste, 3% of automobile waste and metal, 1% of electrical waste, and 54% of other mixed waste, as shown in Fig. 1 [2].



1.1 Waste collection and transportation

The Waste Management Regulation Department of the Office of the Mayor of Ulaanbaatar is responsible for collecting, transporting and other waste-related activities in Ulaanbaatar. It is mentioned that 85% of the total waste in Ulaanbaatar is collected through solid waste management [3]. Waste is collected using manual and mechanical methods and loaded into garbage trucks. As of 2018, there were 298 trucks, however, only 70-85% of them were working properly [4]. During the waste collection, workers use shovels, paper bags, plastic containers, and metal containers when wastes are collected manually. Only the Department of Urban Improvement uses mechanical loaders to collect and load waste from public areas. There are many types of waste collection, such as door-to-door, central collection sites, street-side containers, and scheduled collection. The waste collection varies depending on the location. For example, in apartments, waste is collected one to two times per week, and in ger areas, it becomes one to two times a month. Mostly, wastes are collected manually from garbage cans and residential bunkers. A total of 27 waste collection and transportation companies formerly known as Tohijilt Uilchilgeenii Kompani (TUK) operate in nine districts of Ulaanbaatar. It includes 20 public enterprises and 7 private enterprises.

1.2 Waste disposal

Waste garbage trucks go directly from the source to the disposal sites. To determine the amount of waste delivered to the disposal sites, workers weigh the truck with waste and subtract it from the empty truck weight. Every day, at least three people work at each disposal site: a waste compactor operator, an operator and a technician. However, the number of staff working on those disposal sites could change depending on the upcoming vehicles and waste amount.

There are 6 centralized landfills in 9 districts of Ulaanbaatar. Nalaih, Baganuur and Bagahangai districts have their disposal points. Other 3 centralized disposal points such as Narangiin Enger, Tsagaan Davaa and Moringiin Davaa receive waste from the closest districts (Table 1). Unfortunately, most landfills use the reserve area, and the utilisation rate of the area is more than 80%. Moreover, problems such as open garbage disposal and unsanitary landfills have many negative consequences, affecting groundwater, surface water, odours, and increasing infectious diseases. Additionally, they are facing technical problems such as no fences around disposal points, which cause the waste to spread through the place, no waste sorting lines, inadequate equipment, etc.

Table 1. Summary of disposal sites

Disposal Site Name	Districts	Location	Total area /hectares/	Amount of waste received tons per month
Narangiin Enger	Songinokhairkhan, Bayangol, Chingeltei	32nd districts of Songinokhairkhan	90	13,000- 16,500
Tsagaan Davaa	Bayanzurkh, Sukhbaatar	24th district of Bayanzurkh	90	30,000- 40,000
Moringiin Davaa	Khan- Uul	12th district of Khan-Uul	90	15,000- 17,000

1.3 Waste treatment

In the waste management of Ulaanbaatar city, there is no separation or sorting of waste at any level. However, informally, waste is segregated in several ways. For example, citizens will separate their waste at home, TUK workers will separate the waste during collection, and scavengers will manually collect the recyclable from the waste transported to the disposal sites. A study showed 3% of ger areas and 9% of apartments waste were collected and sent to the market for recyclables [5]. At the same time, TUK workers collected 1.3% of waste from apartments and commercials and 2% from ger areas (ash excluded) into the recycling stream. Moreover, scavengers collect 1.15% recyclables of the incoming waste to the landfill and submit it to recycling markets [3]. It is mentioned sorting, collection, and transportation activities in 2021 individuals and other industrial workers collected an average of 42 kilograms of plastic per day [6]. Ulaanbaatar household waste composition study mentioned that 300,000 tons of waste are sorted annually, representing 8.9% of the total waste generated [7]. Unfortunately, these data vary depending on the source and will not express the actual situation.

In Ulaanbaatar, there are about 200 points of raw materials collection companies, including 24 plastic recycling factories, all of which are members of the Mongolian National Association for Recycling of Waste. It has been seen that plastic recycling industries are included in sourcing secondary raw materials directly and from secondary raw material points. However, due to rent and hygiene requirements, most factories are in the remote area of Ulaanbaatar, not in the city center. Each point of raw materials can receive 60-20,000 kg per day. The purchase price varies depending on the raw material, and the purchase price of plastic is 100-450 MNT/kg for PET, 400-700 MNT/kg for HDPE, 300-600 MNT/kg for other plastics and 500 to 800 MNT/kg for other plastics [6].

2 Methodology

The methodology employed in this study integrates LCA with site selection through suitability analysis utilizing ArcGIS to construct and assess sustainable municipal solid waste management in Ulaanbaatar, Mongolia. LCA evaluates analysis across several scenarios and compares them within specific environmental contexts (global warming potential and biochemical oxygen demand), whereas site selection identifies appropriate locations for different treatment facilities in accordance with LCA findings.

2.1 Life Cycle Assessment

LCA is used to analyze each life cycle phase, from raw material acquisition until final disposal, including all the processes such as manufacturing, distribution, usage, and potential reuse/recycling. In this study, the IWM-II computer model is used. Inputs such as waste and energy and outputs such as recovered energy, recovered materials, compost, air emissions, water emissions and residual solid waste are included in the system boundaries of this model. Each unit process is conducted on a mass basis, except for heat treatment, which is performed on both mass and stoichiometric bases. Landfill gas and leachate are assigned component-specific, reflecting the inherent physical relationship between landfilled waste and gas and leachate production. The possible benefits and drawbacks of alternate scenarios in Ulaanbaatar were evaluated by creating a life cycle inventory model of the current waste management system. After that, additional waste management scenarios were proposed based on the "Vision-2050" National policy and possible recyclable waste amounts in the system region. The following presents an outline of the baseline scenario and the proposed scenarios:

Baseline scenario: 100% Unsanitary landfill

This scenario expresses the current situation of Ulaanbaatar city. Total waste generation per year in Ulaanbaatar is 1,377,635 tons. All the wastes are mixed and treated in unsanitary landfill.

Scenario 1 (S1): 100% Sanitary landfill

The input is the same as in the baseline scenario; however, sanitary landfill is applied. Sanitary landfill is assumed as 90% landfill gas collection, 95% leachate collection and leachate treatment efficiency. For the following scenarios, the sanitary landfill is considered the same as described here.

Scenario 2 (S2): 10% MRF+ 90% Sanitary landfill

50% of household waste and 60% of commercial waste is collected using Kerbside collection. Recyclables such as paper, glass, metal, plastic and textiles treated in MRF, and the rest of the waste goes to sanitary landfills.

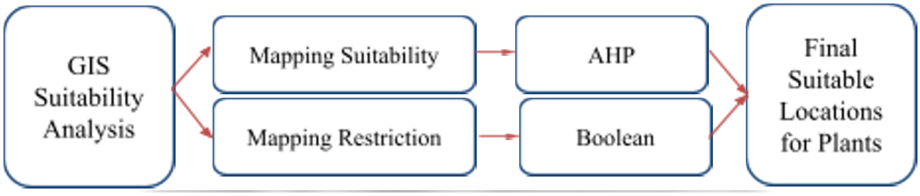
Scenario 3 (S3): 15% MRF+ 7% RDF+ 78% Sanitary landfill

60% of household waste, 70% of commercial waste is collected using Kerbside collection. Glass, metal and plastic are recycled, which are 15% of waste and 7% of the waste including paper and textile goes to RDF with 15% of gross efficiency of energy recovery and the rest of the waste is treated in sanitary landfill.

Scenario 4 (S4): 20% MRF+ 7% Composting+ 7% RDF+ 66% Sanitary landfill

80% of both household and commercial waste is collected, however, paper and textiles are collected Material Bank collection and rest of the waste is collected by Kerbside collection. In MRF, glass, metal and plastic are recycled. In composting, only commercial organic waste is composted with 50% mass loss and 100% marketable and 7% of waste which are paper and textile go to RDF and remaining wastes are treated in sanitary landfill.

2.2 Geographic Information System



The Analytical Hierarchy Process (AHP) is a fundamental methodology for decision-making. It is built to address both rational and intuitive processes to identify the optimal choice among several options assessed against multiple criteria. The decision maker performs pairwise comparison assessments, which are subsequently used to establish general priorities for ranking the alternatives based on the criteria. The overall workflow of the suitability analysis based on AHP is presented in Fig.2. In this study, criteria are road, slope and elevation and alternatives are collection efficiency, safety and cost minimization. The criteria used in AHP are chosen due to the objective of the study. For waste management facilities, closer proximity to road is a critical factor for enhancing collection efficiency, as waste transport vehicles require reliable and accessible routes to minimize fuel consumption, reduce collection time, and improve service efficiency. For safety, lower altitudes and gentler slopes contribute to enhanced security.

After setting the hierarchy of the study, pairwise comparison matrix is set to determine the weights of the criteria [8] using the fundamental scales [9]. The weights of the criteria of the study are shown in Table 2.

Table 2. Weight and criteria for all facilities

Criteria	Weight
Road	0.5
Slope	0.2
Elevation	0.3

However, during the calculation inconsistency occurs. To check the calculated weights of the consistency, a consistency ratio (CR) is used. When the value of CR is more than 0.10, it indicates an unacceptable level of inconsistency. In this study, CI is 0.01936, RI is 0.58 and CR is 0.03337.

Restriction Model

This model was implemented by incorporating specific constraints and filters, ensuring that the analysis exclusively included areas conforming to legal, environmental, and logistical requirements [10]. This study's criteria for MRF, RDF, and Compost are decided based on previous studies [11,12,13].

Table 3. Restriction map criteria for facilities.

Criteria		MRF Buffer Applied (m)	RDF Buffer Applied (m)	Composting Facility Buffer Applied (m)
Waterbodies	River, waterline, water area	100	100	200
Roads	Roads	40	30	30
	High rails	150	150	150
Land use	Household	100	100	150
	Commercial, construction, industrial	50	100	150
Building		300	300	300

Finally, the final suitability map for potential sites will be created using the restriction models and weight for criteria.

$$S = \sum_{i=1}^{n} Wi \times Ci \prod_{j=1}^{n} rj \#(1)$$

Where S = Suitability for Case Study

Wi = Weight for Criteria
Ci = Criteria for Suitability
rj = Restriction Criteria

3 Results and Discussion

3.1 Life Cycle Assessment

The baseline scenario expresses the current condition of Ulaanbaatar city based on waste generation and treatment. The total final solid waste is 1,377,664 tons, with 710,040 tons of GWP and 144.5 tons of BOD. However, S1 applied sanitary landfill, and it reduced the GWP by 69.1% and reached 219,417 tons and the BOD by 90.2% and reached the lowest BOD emissions of all scenarios, which is 14.1 tons. With the same input, sanitary landfills show significant environmental improvements in terms of environmental indicators compared to the base scenario.

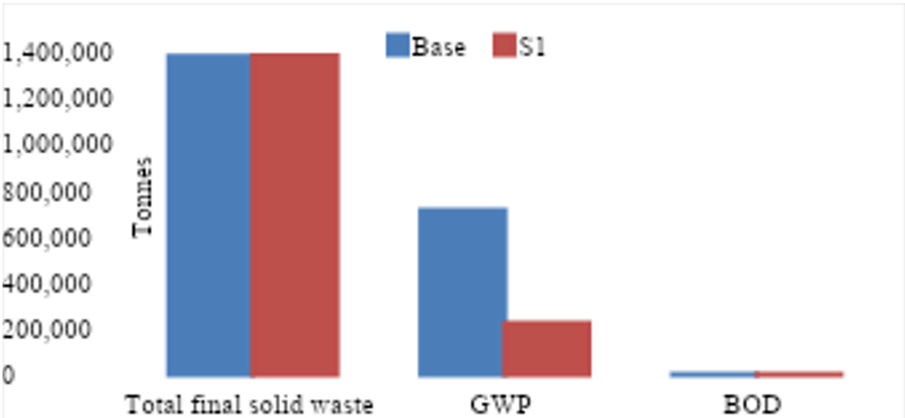
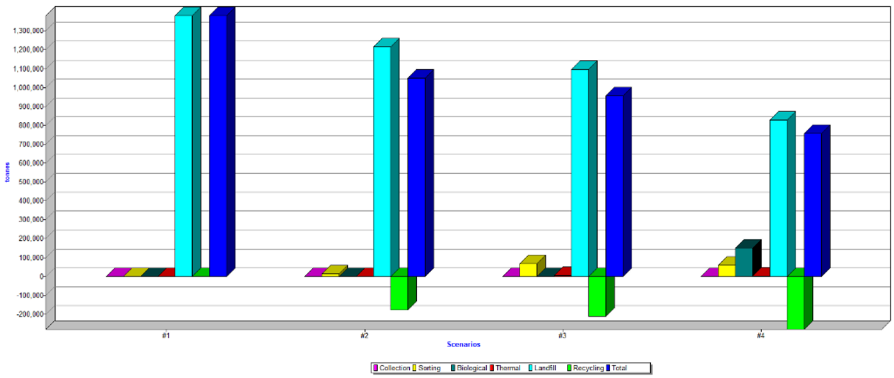
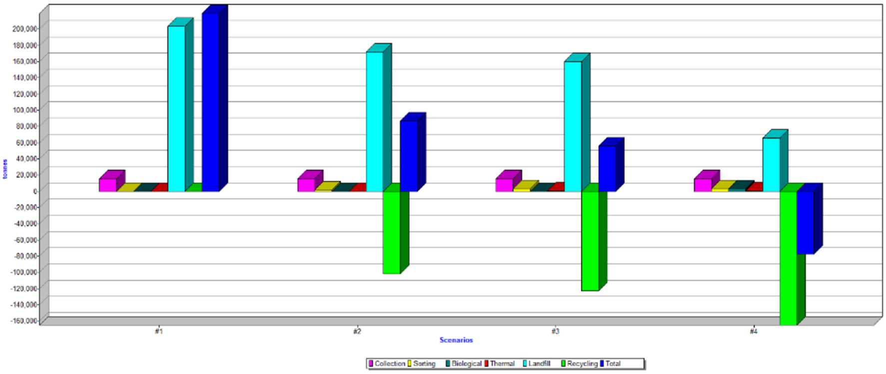


Fig. 3. Comparison of baseline scenario and S1

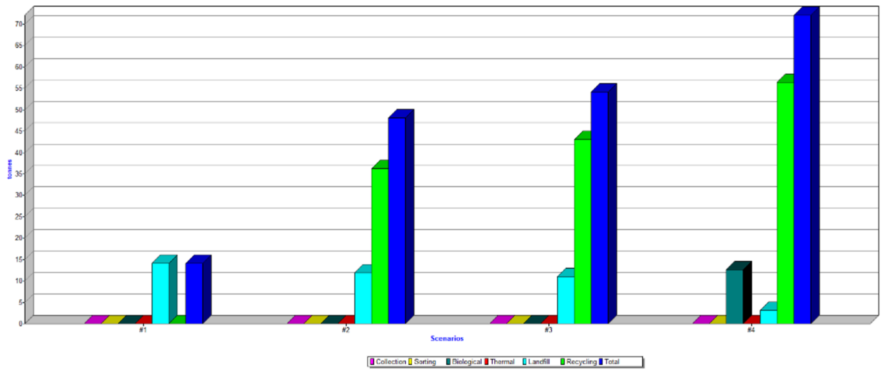
For the total final solid waste (Fig. 4), S4 has the lowest final waste due to the high recycled amount and biological and thermal treatment and reached 757,529 tons which is 45% lower than the baseline scenario. S3, S2 have also a slight decrease in



total waste 30.6% and 23.7% respectively. Lastly, S1 did not have any change in total waste because it did not apply any treatment. In Fig. 5, it shows GWP of the proposed



scenarios. Among the scenarios, S4 has the most impact which is 77,359 tons of net

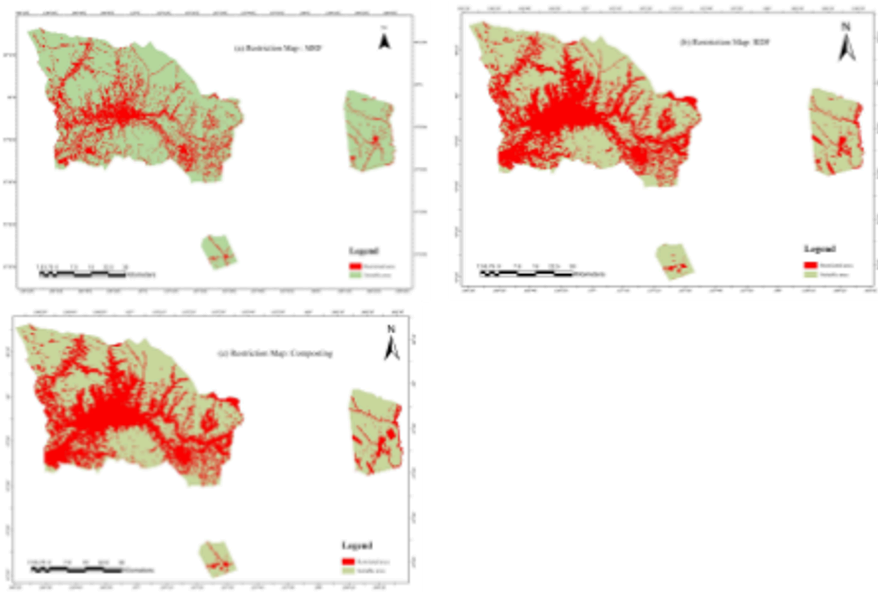


reduction of greenhouse gas. The recycling amount lowers the GWP by 165,057 tons which brings a positive impact to the GWP. In S3 and S2, it lowers GWP up to 55,625 tons (92%), 87,166 tons (88%) lower than the baseline scenario respectively. S1 also minimizes the GWP by 69% because of the sanitary landfill improvements. In the BOD analysis (Fig. 6), S1 achieves the lowest value, reducing BOD by 90% from the baseline scenario. In S2 and S3, moderate improvements are seen such as 67% and 62.5% reduction respectively. S4 was the least effective with only 50% reduction.

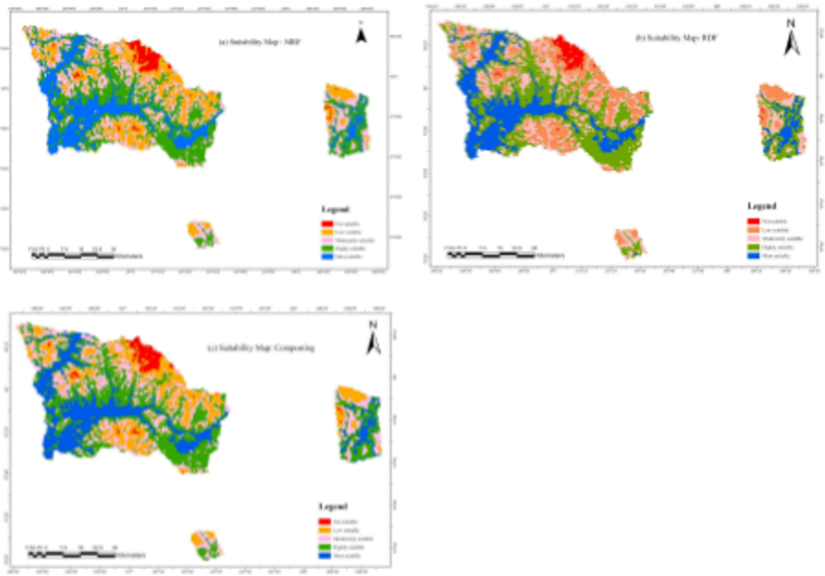
Fig 6. BOD of proposed scenarios

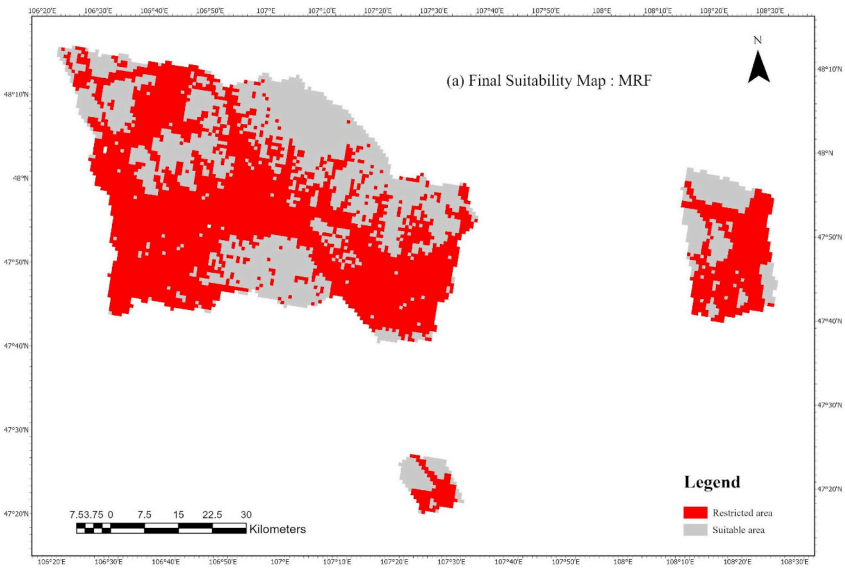
3.2 Identification of suitable locations for waste management facilities by GIS

This section includes the results of the GIS analysis, including a restriction map, suitability map, and final suitability map for all facilities, which are MRF, RDF, and composting facility. In Fig. 7, final restriction maps of all facilities are shown. Criteria including waterbodies, roads, land use and buildings are considered. The red color in the map indicates the restricted area whereas the green color shows suitable area for the facilities.



The suitability map has 5 classifications, including not suitable, low suitable, moderately suitable, highly suitable, and most suitable. Due to the increased weight of roads, the most appropriate locations are typically situated in low-lying areas close to rivers, roadways, and industrial areas. Each facility's suitability map is illustrated in Fig. 8.


N
Legend


(a) Final Suitability Map : MRF
N
Legend
Restricted area
Suitable area
7.53.75 0 7.5 15 22.5 30
Kilometers
106°20'E 106°30'E 106°40'E 106°50'E 107°E 107°10'E 107°20'E 107°30'E 107°40'E 107°50'E 108°E 108°10'E 108°20'E 108°30'E
48°10'N 48°N 47°50'N 47°40'N 47°30'N 47°20'N

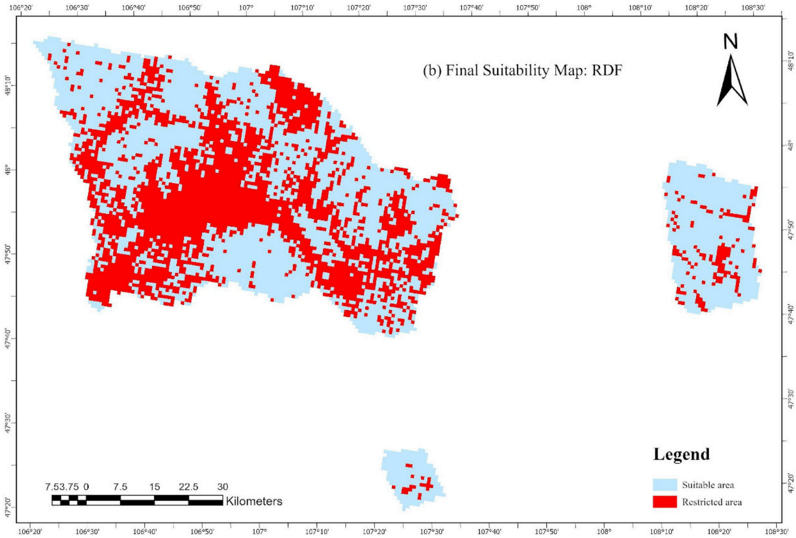


Fig. 10. Final suitability map of RDF based on restriction and suitability

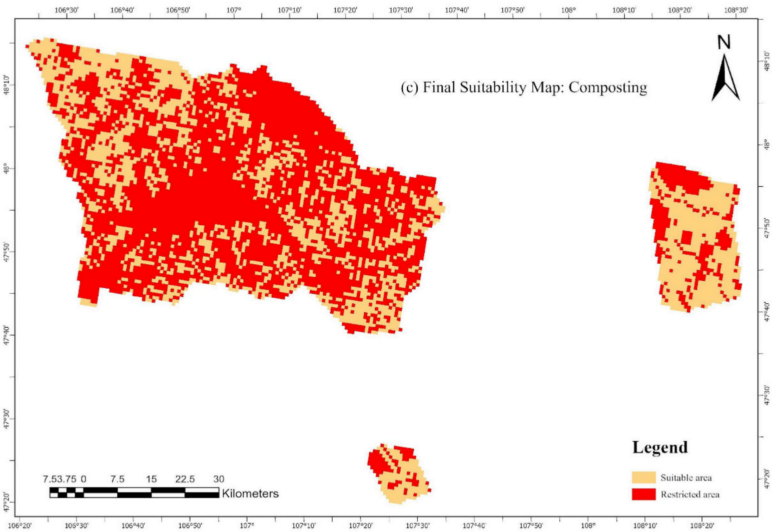


Fig. 11. Final suitability map of Composting based on restriction and suitability

In Figs. 9-11, the final suitability map is created by combining a restriction map and a suitability map of only the highly suitable and most suitable areas. Based on Fig. 9, the suitability analysis has been conducted across nine districts of Ulaanbaatar City, revealing that the most suitable locations for MRF are sited in the Khan-Uul, Bayangol, and Songinohairkhan districts. These districts are located near major roadways, facilitating efficient waste transportation and the return of recycled materials. Moreover, it is shown that locating in central districts and being close to residential and commercial zones, in proximity to primary waste sources such as the industrial sector will minimize transportation costs and environmental impact. In Fig. 10, the most suitable locations for RDF plants are in districts of Bayangol, Chingeltei, Sukhbaatar and Khan- Uul. Three thermal power plants of Ulaanbaatar are in Bayangol and Khan-Uul districts. Thus, establishing RDF in those districts could also support electric and thermal power plants by providing a reliable alternative fuel source that reduces waste while generating energy. Fig. 11 shows a suitable area for composting facilities which is also around six central districts. Like the previous two facilities, areas that are situated at a considerable distance from residential neighborhoods, to mitigate odor-related concerns, and those near water sources to facilitate efficient transportation, are considered suitable locations for composting plants.

4 Conclusion

In the analysis of LCA, 5 scenarios are analyzed in terms of final solid waste, BOD, GWP. The current situation of Ulaanbaatar city is modelled as a baseline scenario. The total final solid waste is 1,377,664 tons, with 710,040 tons of GWP and 144.5 tons of BOD. S1 applied a sanitary landfill of the same input as the baseline scenario, reducing the GWP by 69.1%, reaching 219,417 tons and the BOD by 90.2%, and reaching the minimum emission of 14.1 tons of BOD. From here, it is known that sanitary landfills greatly benefit the environment, including air and water emissions.

According to the LCA result, among all the scenarios, S4 specifically 20% MRF+ 7% Composting+ 7% RDF+ 66% Sanitary landfill has offered the best balance achieving low final waste (757,529 tons), low GWP (-77,35 tons) and moderate improvement in BOD (72 tons). Compared with the other proposed scenarios, the final total solid waste in S4 was reduced by 45.1% relative to S1, 27.9% relative to S2, and 20.8% relative to S3. Furthermore, S4 was the only scenario that avoids GHG emissions seen as the most sustainable for future implementation.

In the analysis of GIS, suitability maps have been generated to guide officials in selecting the best possible area for facilities such as MRF, RDF, and composting sites by integrating various spatial analyses and criteria. The analysis has identified suitable areas within nine districts of Ulaanbaatar City for waste management facilities. It is seen that six central districts are the appropriate sites for all facilities in detail; the districts of Khan-Uul, Bayangol, and Songinohairkhan emerge as favorable for MRF due to their strategic location near major transportation routes and waste sources, ensuring efficiency and cost-effectiveness. For RDF plants, Bayangol, Chingeltei, Sukhbaatar, and Khan-Uul are recommended, with their proximity to thermal power plants providing an added benefit of integrating waste-to-energy solutions.

Composting facilities are best situated in central districts, balancing distance from residential areas to address odor concerns while maintaining accessibility to water resources.

In conclusion, this study offers a sustainable and low-environmental-impact waste management scenario, locates the factories mentioned in the scenarios, and proposes a comprehensive plan to decision-makers based on the current situation of Ulaanbaatar city.

4.1 Recommendation and limitations

First, this research has several limitations due to the data on MSW in Ulaanbaatar. There is no data source on household and commercial waste composition, as all waste is collected as mixed waste. Thus, the household waste composition is assumed based on the Asian Foundation Household study [7]. In contrast, commercial waste composition is estimated using national commercial waste data from the Mongolian Statistical Information Service. These assumed waste compositions could affect the result of LCA calculations. If the actual waste compositions contain more recyclables than assumed, scenarios that emphasize recycling could achieve even greater reductions in GWP and lower final solid waste. Conversely, if organic waste is higher than estimated, scenarios that rely on landfills may produce more greenhouse gas emissions than predicted, potentially altering the relative rankings of the scenarios. This highlights the need for future research focused on detailed waste composition studies. Another limitation of the data is the recycling amount in Ulaanbaatar city. Even though mini-private companies recycle a small amount of waste, they cannot show how many tons or what percentage of waste they recycle. Consequently, in the baseline scenario, the recycling amount is considered as zero. In the future, to improve the database, record data using a standard format, ensure regular data submission by all companies and organizations, and implement a centralized database managed by city authorities. Additionally, informal recycling in Ulaanbaatar could be better integrated into formal systems through several approaches. These include providing incentives to recyclers who join the formal system, offering tax deductions, and developing information and data platforms to support their activities [14].

In the data analysis, first LCA and then spatial analyses are done. Thus, the LCA analysis lacks consideration for networking, particularly waste collection networks and transportation routes, which are significant sources of emissions and environmental impacts. The distance of each facility was assumed to be the average distance to the current three landfill sites, which are 20 km. This could be a limitation of the study, and in future research, a detailed distance to each facility or analysis of both data at the same time is recommended.

Lastly, IWM-II software lacks an integrated sensitivity analysis feature. It also has a few options for environmental impacts, including only air and water emissions. This indicates that outcomes derived from identical scenario requirements with a different software would be different [15].

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