Journal of Science and Technology in Civil Engineering, HUCE, 2026, 20 (2): 60–75

GREENHOUSE GAS EMISSIONS MITIGATION IN MUNICIPAL SOLID WASTE COLLECTION SYSTEMS

Trinh Bao Khanh[a], Hoang Minh Giang[a,*], Vu Viet Ha[a], Nguyen Huong Giang[b]

[a] *Faculty of Environmental Engineering, Hanoi University of Civil Engineering,*
55 Giai Phong street, Bach Mai Ward, Hanoi, Vietnam
[b] *School of Chemistry and Life Science, Hanoi University of Science and Technology,*
1A Dai Co Viet road, Bach Mai Ward, Hanoi, Vietnam

Article history:
Received 12/11/2025, Revised 17/12/2025, Accepted 11/02/2026

Abstract

Greenhouse gas (GHG) emissions from the collection and transfer operations are a significant component within any municipal solid waste (MSW) system. This has not been optimally studied in previous works. The present study aims to quantify current GHG emissions from the MSW collection system in the central area of Hanoi and to develop alternative operational scenarios for GHG mitigation. Operational data on waste-collection vehicles and the transfer station (TS) were obtained from waste collection company's digital maps and reports. The United Nations Environment Programme's Emission Quantification Tool (EQT) Version III was ultilized for GHG emissions. The research evaluates various collection scenarios while incorporating TS location to determine an optimal distance that aligns with cost and GHG emissions targets. In the study area, the waste collection and transportation system covers an average daily travel distance of 2,167.68 km, utilizing a fleet of vehicles with capacities ranging from 1 to 11 tonnes. As a result, the system generates approximately 28 kg CO_2-eq per tonne of MSW. At present, the waste transfer process in the study area remains inefficient. The proposed TS achieves about a 21.5% reduction in GHG emissions relative to the existing facility. Two key factors contributing to emission reduction are the minimization of transport distance and the use of fuel-efficient vehicle types. Among all scenarios, employing TS consistently proves to be a more effective option than direct transportation to the Nam Son Waste Treatment and Disposal Complex. TS should be located along the shortest route between the collection areas and the treatment complex, preferably as close to the collection areas as possible to minimize transportation distance and cost. These results give scientific proof to back MSW planning and optimization aimed at the net-zero emission goal in the MSW management field.

Keywords: greenhouse gas emissions; municipal solid waste; waste transfer systems; transfer station; optimization of transfer distance.

https://doi.org/10.31814/stce.huce2026-20(2)-05

1. Introduction

The IPCC AR6 report has confirmed that climate change and global warming are among the most critical challenges facing nations worldwide [1]. The report also emphasized that human-induced climate change has contributed to the increasing frequency and intensity of extreme weather events across all regions, resulting in widespread impacts on ecosystems and human communities [1]. Global warming has thus become a major concern for countries around the world [2]. The uncontrolled use of fossil fuels is one of the main drivers of the rise in GHG emissions, leading to global warming and increasingly severe climate change [3]. The MSW management sector has been identified in numerous studies as a significant source of GHG emissions, accounting for approximately 3% of global GHG emissions [4]. Research conducted in major cities indicates that emissions from MSW

---

[*] Corresponding author. *E-mail address:* gianghm@huce.edu.vn (Giang, H. M.)

management systems are increasing rapidly. For instance, in Beijing, the total GHG emissions from the city's MSW management system doubled in just over a decade, rising from 3.62 million tonnes CO_2 to 6.57 million tonnes CO_2 in 2019 [5]. In developed countries such as the United States, GHG emissions from the MSW management system reached 169.2 million tonnes in 2021, equivalent to the annual electricity-related emissions of approximately 30 million households [6, 7]. To put this into perspective, one million tonnes of CO_2 is equivalent to burning over 400 million liters of gasoline, and it would take 16.5 million trees over ten years to absorb that amount of CO_2 [7, 8].

Nowadays, with the rapid expansion of urban areas, MSW management has become one of the key factors associated with the sustainable development goals of cities. MSW collection and transportation are indispensable components of the overall MSW management system [9, 10]. However, most current studies on emissions from MSW management have primarily focused on treatment processes, technology selection, or route optimization, while the transfer and transportation stages have not yet been adequately optimized to reduce GHG emissions [10, 11]. These stages consume a substantial amount of energy and fossil fuels, leading to significant GHG emissions [12]. This highlights a research gap in optimizing GHG emissions from MSW transfer and transportation systems.

A typical example can be found at the Hanoi Urban Environment Company (URENCO), where there is an urgent need to analyze, assess, and optimize scenarios for the transfer and transportation of MSW. Selecting an appropriate transportation option not only influences operational costs but also has a significant impact on GHG emissions and short-lived climate pollutants (SLCP) generated during waste transfer and transportation activities. Similar challenges are being faced not only in the study area but also in many major cities and urban regions under planning and development. Developing evaluation models and optimization approaches for MSW transfer and transportation systems can support decision-making in TS planning, reduce GHG emissions, and contribute toward achieving low-carbon urban development. As Vietnam has committed to achieving net-zero emissions by 2050 under the Paris Agreement and the National Climate Change Strategy, the quantitative assessment of GHG emissions from MSW transfer operations becomes particularly essential [13].

Building upon the aforementioned issues and identified research gaps, this study aims to evaluate GHG emissions generated from MSW collection, transfer, and transportation activities. On this basis, several operational scenarios of the transfer system are developed and compared to identify the recommended option for the study area. The findings are expected to provide scientific evidence to support decision-making in the management and planning of MSW collection and transfer systems. In addition, the study contributes to assisting environmental management agencies and public service enterprises in reducing emissions and advancing toward the net-zero emission target.

2. Methodology

2.1. Study area and current status of MSW management

a. Study area

In this study, the selected survey area corresponds to the MSW collection zone managed by URENCO Branch 2, covering Hoan Kiem District, Hanoi (currently including Hoan Kiem ward, Cua Nam ward and a part of Hong Ha ward). This area represents the economic, political, cultural, and administrative center of the capital city, and it also contains numerous historical sites and major tourist attractions. With an area of only 5.34 km^2 and a population of 212921 inhabitants, Hoan Kiem is a small district characterized by a high population density and the presence of many governmental institutions and key transportation hubs [14]. According to data from URENCO, the amount of MSW generated in the district is approximately 158 tonne/day, corresponding to an average generation rate of 0.74 kg/person/day [15].

b. Current status of MSW management

The local waste management company currently operates a total fleet consisting of the following vehicles: 8 units of small trucks (1-tonne capacity, with 4 out of 8 in operation); 5 units of 2.5-tonne trucks (4 out of 5 in operation); 14 units of compactor trucks (5–10-tonne capacity, with 7 out of 14 in operation); 4 units of container/hooklift trucks (11-tonne capacity, with 2 out of 4 in operation); and 1 unit of sensor-equipped vehicle (1-tonne capacity). The reported waste collection rate reached 96% in 2023, with a target of achieving 100% collection coverage by 2050 [15].

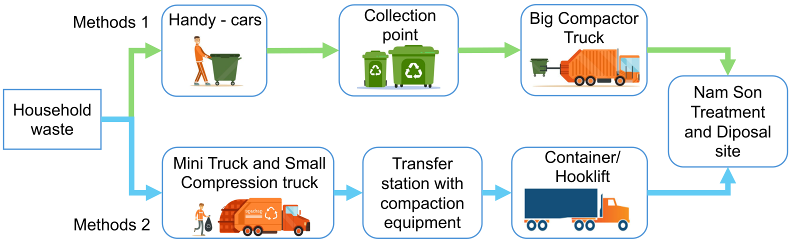


Figure 1. Diagram of the current status of MSW transportation in the study area

The current MSW collection and transportation system in the study area is illustrated in Fig. 1, comprising two main methods. In the first method, household waste is collected using handy-carts and gathered at designated public collection points. From there, the waste is transported directly to the Nam Son Waste Treatment and Disposal Complex by large compactor trucks. In the second method, waste is collected using small trucks or mini compactor trucks and transported to TS equipped with waste compaction facilities. At the station, the waste is compressed and then hauled to the Nam Son Waste Treatment and Disposal Complex by container trucks or hooklift trucks with a load capacity of 11 tonnes.

2.2. *Optimal distance determination for TS siting*

a. TS located on the shortest route to the disposal site

When TS is located along the shortest route connecting the waste generation area to the disposal site, the optimal distance can be determined using the method proposed by Ouano (1983) [16]. The condition for the optimal distance to be satisfied is expressed by the Eq. (1):

$$Y \geq \frac{B}{2(A - C)} \tag{1}$$

where Y is the distance from TS to the disposal site (km); A is the unit transportation cost for small trucks or compactor trucks, calculated from the collection point to TS (VND/tonne-km); C is the unit transportation cost for container or hooklift trucks, calculated from TS to the disposal site (VND/tonne-km); and B is the operating cost of TS (VND/tonne). This equation is independent of the distance between the collection point and TS.

b. TS not located on the shortest route to the disposal site

In cases where TS is not located along the shortest route, the transportation distance must follow a longer path. This situation may arise due to the high land prices near the city center or because the area is unsuitable according to the city's planning regulations. In such cases, the optimal distance for locating TS can be determined using the formula proposed by Ouano (1983) [16]. The optimal distance must satisfy the Eq. (2):

$$Y \geq \frac{B + 2A\Delta X + 2C\Delta Y}{2(A - C)} \tag{2}$$

where Y is the distance from TS to the disposal site (km); A is the unit transportation cost for small trucks or compactor trucks, calculated from the collection point to TS (VND/tonne-km); C is the unit transportation cost for container or hooklift trucks, calculated from TS to the disposal site (VND/tonne-km); and B is the operating cost of TS (VND/tonne). This equation is independent of the distance between the collection point and TS.

2.3. Data collection and processing

a. Average travel distance per collection trip

Data on the travel distances of MSW collection and transportation vehicles were obtained from the vehicle tracking system (BA GPS). The data files, exported in Excel format, were provided by the local waste management company for this study. The dataset reflects waste collection activities within the operational area managed by the local waste management company. Specifically, it includes the daily travel distances of each vehicle type over a 31 day period, from July 1, 2025 to July 31, 2025. For each vehicle category, a total of 31 observation samples were collected for analysis. In the case of compactor trucks with load capacities ranging from 5 to 10 tonnes, the BA GPS system did not specify each vehicle type. Therefore, an average load capacity of 7.5 tonnes was adopted for the calculations.

During raw data processing, outliers were identified using the Interquartile Range (IQR) method by establishing the lower and upper fences. Values falling outside this range were considered outliers and were adjusted through the Winsorization method, in which outliers were replaced with the nearest boundary values. This step ensured the stability of the dataset and the removal of extreme values. From the adjusted dataset, the daily transportation distance was divided by the distance of a single trip (as recorded by the BA GPS tracking system) to determine the number of trips made per day by each vehicle. Finally, the average travel distance per trip for each vehicle type was calculated by dividing the average total daily distance over the 31 day period by the corresponding average number of trips.

After collecting data on the average transport distances of five vehicle types: (i) small trucks (1 tonne), (ii) small compactor trucks (2.5 tonnes), (iii) sensor-equipped trucks (1 tonne), (iv) large compactor trucks (7.5 tonne), and (v) container/hooklift trucks (11 tonnes). The first three types were grouped into the category of "mini trucks and small compactor trucks". The calculation parameters for this group were determined based on the average values of the three corresponding vehicle types. The average daily transport distance was calculated as the product of the average one-way distance per trip and the number of trips performed per day. The number of trips was estimated based on the ratio between the total waste mass to be transported and the vehicle's rated load capacity. Within the scope of this study, the increase in transport distance due to changing truck capacity from 7.5 tonnes to 10.5 tonnes was not considered. The waste collection distance was defined as the distance from the first to the last collection point along the route. For large compactor trucks, the average collection distance was 11.5 km, determined from GPS data provided by the local waste management company.

b. Determination/calculation of unit cost

The unit cost in this study was determined based on the current regulatory documents in Vietnam. The transportation cost of MSW comprises two main components: (i) labor cost and (ii) fuel cost. The labor cost was calculated according to the number of workers specified in Decision No. 50/2025/QĐ-UBND of Hanoi City and Circular No. 36/2024/TT-BTNMT [17, 18], combined with the basic salary level regulated in Circular No. 17/2019/TT-BLĐTBXH and Decree No. 204/2004/NĐ-CP [19, 20]. The fuel cost was determined by multiplying the fuel consumption rate (as prescribed in Circular No. 36/2024/TT-BTNMT) with the actual fuel price. In this study, the fuel used for waste collection and transport vehicles was Diesel DO 0.001S-V, with an assumed average price of 19 thousand VND/liter. All cost estimations were adjusted using distance-based coefficients, with one coefficient applied for every 5 km range. For the TS unit cost, the total cost consists of three components: (i) operational labor cost (including compaction, weighing, deodorization, vehicle routing, exhaust gas treatment, and wastewater treatment), (ii) electricity consumption, and (iii) depreciation cost. The operational labor cost at TS was calculated according to Decision No. 50/2025/QĐ-UBND of Hanoi City and Circular No. 36/2024/TT-BTNMT, in combination with the wage level stipulated in Circular No. 17/2019/TT-BLĐTBXH. Electricity consumption at TS was assumed at 2.5 kWh/tonne [21]. Depreciation costs were calculated in accordance with the classification of tangible fixed assets specified in Circular No. 23/2023/TT-BTC [22]. The depreciation cost was calculated based on the classification of tangible fixed assets regulated in Circular No. 23/2023/TT-BTC, with a depreciation rate of 95.89 thousand VND/tonne.

All unit costs in this study were adjusted using distance-dependent correction factors. These factors are specified for discrete distance intervals, typically ranging from 5 to 15 km per interval. Although this interval-based approach reflects government-regulated cost levels, it does not capture the incremental change in unit cost per kilometer. Therefore, the study employs a linear regression model based on the correction factors stipulated in the current pricing framework. The correction factors for each distance level are treated as discrete, stepwise data points as defined by the regulatory documents. To construct a continuous function that better represents the trend of cost adjustment with increasing transport distance, a linear regression model with a zero-intercept constraint is applied. This constraint reflects the economic nature of the adjustment factor, whereby a transport distance of zero results in a unit cost of zero.

2.4. *Scenarios development*

The scenarios were developed to evaluate and select the optimal options for MSW collection and transportation in terms of both cost and emissions. Several of these scenarios were also formulated based on the operational orientation of the local MSW management company, which is currently assessing two alternatives: (i) using 10.5-tonne compactor trucks for direct collection and hauling to the Nam Son Waste Treatment and Disposal Complex, and (ii) utilizing TS, followed by transport to the treatment complex using 11-tonne container/hooklift trucks. When the collection truck load reaches 10.5 tonnes, the difference in transported mass between the two vehicle types is negligible. However, their operational processes and fuel consumption rates differ considerably. In addition, the optimization of collection vehicle types was integrated into the scenarios for evaluation. Generally, smaller trucks consume less fuel, whereas larger trucks have higher fuel consumption but can transport a greater amount of waste per trip. Therefore, a comprehensive assessment is required to identify the vehicle type and system configuration that deliver the most efficient operational performance.

Currently, the location of the Lam Du TS is not situated along the shortest route to the waste treatment complex, resulting in suboptimal operational efficiency. From a technical perspective, TS should be located along the shortest possible route to the treatment facility and as close as feasible to the collection area. From a regulatory perspective, according to Decision No. 1668/QĐ-TTg approving the general planning of Hanoi City, TS may be located within areas designated for green spaces, parks, or public facilities, provided that odor and leachate control measures are implemented to maintain urban aesthetics. Based on the above technical and legal criteria, this study identifies a proposed site at the intersection of Alley 32 An Duong Street and Hong Ha Street. The area is designated for public service purposes, with a total land area exceeding 1 hectare. Land parcels designated for TS construction were assumed to comply with existing urban planning regulations, with land costs were not considered in the analysis. This selected site serves as a reference case to illustrate the approach for GHG assessment and does not represent a prescriptive recommendation.

Table 1. Description of scenarios

Scenario	Description
Business-as-usual scenario (BAU)	In this scenario, the local waste management company employs two main modes of MSW collection and transportation, with the number of vehicles and their daily operating frequencies summarized as follows: - Four small trucks (1-tonne capacity), operating three trips per day, responsible for collecting and transporting MSW to the Lam Du TS. - Four small compactor trucks (2.5-tonne capacity), operating three trips per day, collecting and transporting MSW to the Lam Du TS. - One sensor-equipped vehicle (1-tonne capacity), operating two trips per day, collecting and transporting MSW to the Lam Du TS. - At the Lam Du TS, the collected waste is compacted and reloaded onto container/hooklift trucks (11 tonnes) for long-distance transport to the Nam Son Waste Treatment and Disposal Complex. - Two container trucks (11-tonne capacity), operating two trips per day, transporting MSW from TS to the Nam Son Waste Treatment and Disposal Complex. - Seven large compactor trucks (7.5-tonne capacity), operating two trips per day, directly collecting and transporting MSW to the Nam Son Waste Treatment and Disposal Complex without using TS.
Scenario 1 (SC1)	Collection and direct transport of MSW using only 10.5-tonne compactor trucks to Nam Son Complex
Scenario 2 (SC2)	Collection of MSW using all small trucks and small compactor trucks to the Lam Du TS; waste is compacted and reloaded onto 11-tonne container/hooklift trucks for transport to the Nam Son Waste Treatment and Disposal Complex.
Scenario 3 (SC3)	Collection of MSW using all 7.5-tonne compactor trucks to the Lam Du TS; waste is compacted and reloaded onto 11-tonne container/hooklift trucks for transport to the Nam Son Waste Treatment and Disposal Complex.
Scenario 4 (SC4)	The hypothetical TS is located 1.5 km from the end-of-route collection point and is situated along the shortest route to the Nam Son Waste Treatment and Disposal Complex. The waste transfer process is described as follows: all 7.5-tonne compactor trucks to the Lam Du TS; waste is compacted and reloaded onto 11-tonne container/hooklift trucks for transport to the Nam Son Waste Treatment and Disposal Complex.

The following parameters were applied consistently across all scenarios: the generation and collection rates of MSW, as well as the composition and physical characteristics of the waste. The fuel consumption rates for different vehicle types were as follows: mini trucks and small compactor trucks (0.1418 L/km); 7.5-tonne compactor trucks (0.8537 L/km); 10.5-tonne compactor trucks

(1.079 L/km); and 11-tonne container or hooklift trucks (0.6428 L/km). All scenarios employing large-capacity compactor trucks were developed based on their operational feasibility. In practice, 7.5-tonne compactor trucks are used for direct transportation to the treatment facility, while 10.5-tonne compactor trucks have been evaluated and deemed suitable by the local environmental company. All vehicles evaluated in the scenarios were assumed to comply with Euro 5 emission standards. The unit transportation cost for each vehicle type was considered identical across all scenarios. The scenarios are presented in Table 1.

2.5. Greenhouse gas emissions assessment method

This study employed the EQT Version III, developed by the Institute for Global Environmental Strategies (IGES) in collaboration with the UNEP and released in 2025 [23]. EQT is an Excel-based computational tool designed in accordance with the methodological guidelines of the Intergovernmental Panel on Climate Change (IPCC). The tool allows users to input activity data related to waste collection and transportation, and then applies either default or country-specific emission factors to estimate emissions. Based on this framework, the present study utilized EQT to quantify GHG emissions from MSW transportation activities, serving as the foundation for analyzing and comparing different waste management scenarios.

3. Result and discussion

3.1. Results of optimal distance determination for TS siting

In calculating the optimal distance, this study assumes that the distance along the collection route is not considered. The distance used in the model is measured from the end point of the collection route, which is defined as the starting point of the transportation segment at the Long Bien Station area. This point is referred to as the “end-of-route collection point” throughout the study. The location was selected because Long Bien Station lies on the boundary of the collection area and represents the nearest point to the Nam Son Waste Treatment and Disposal Complex. GPS route data of collection vehicles also indicate that most vehicles transporting waste directly to the treatment and disposal complex pass through this location. The distances used in the analysis were determined using Google Maps, including: (i) the distance from the end-of-route collection point to the Nam Son Waste Treatment and Disposal Complex, which is 39.5 km; (ii) the distance from the Lam Du TS to the Nam Son Waste Treatment and Disposal Complex, which is 43 km; (iii) the distance from the end-of-route collection point to the Lam Du TS, which is 3.5 km; and (iv) the distance from the end-of-route collection point to the newly assumed TS is 1.5 km. Based on the calculated distances, the values of $\Delta X = 3.5$ km and $\Delta Y = 3.5$ km represent the additional travel distances incurred when transporting waste through the Lam Du TS, compared with the direct hauling option to the Nam Son Waste Treatment and Disposal Complex. Furthermore, the model input parameters were defined based on the Vietnamese regulatory framework governing transportation unit costs and TS operation expenses. Parameter A (the transportation cost for small trucks or compactor trucks) was analyzed in two cases: (i) 7.5-tonne compactor trucks and (ii) 10.5-tonne compactor trucks, with corresponding values of 3.554 thousand VND/tonne-km and 2.938 thousand VND/tonne-km, respectively. Parameter C, representing the transportation cost for 11-tonne container trucks, was set at 1.481 thousand VND/tonne-km. Parameter B, indicating the operating cost at TS, remained constant in all cases, with a value of 115.106 thousand VND/tonne. All unit costs used in the cost-optimization analysis were adjusted using the distance-dependent correction factor. The linear regression equation for the distance-dependent correction factor is presented in Fig. 2.

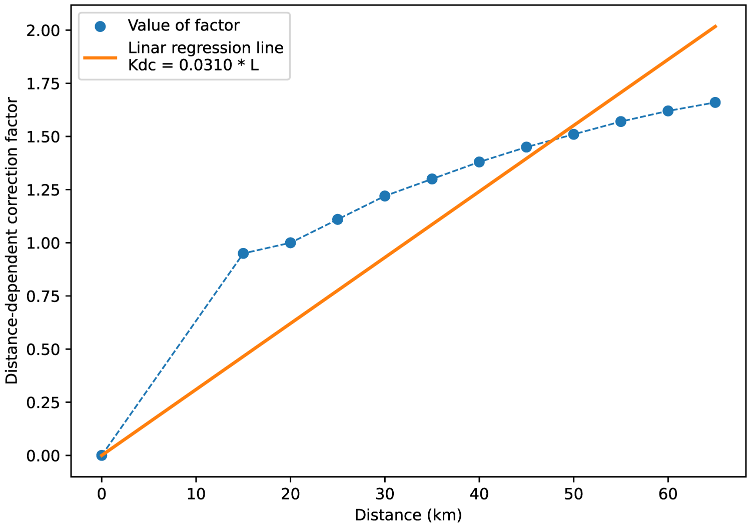


Figure 2. Constrained linear regression of the distance-dependent correction factor

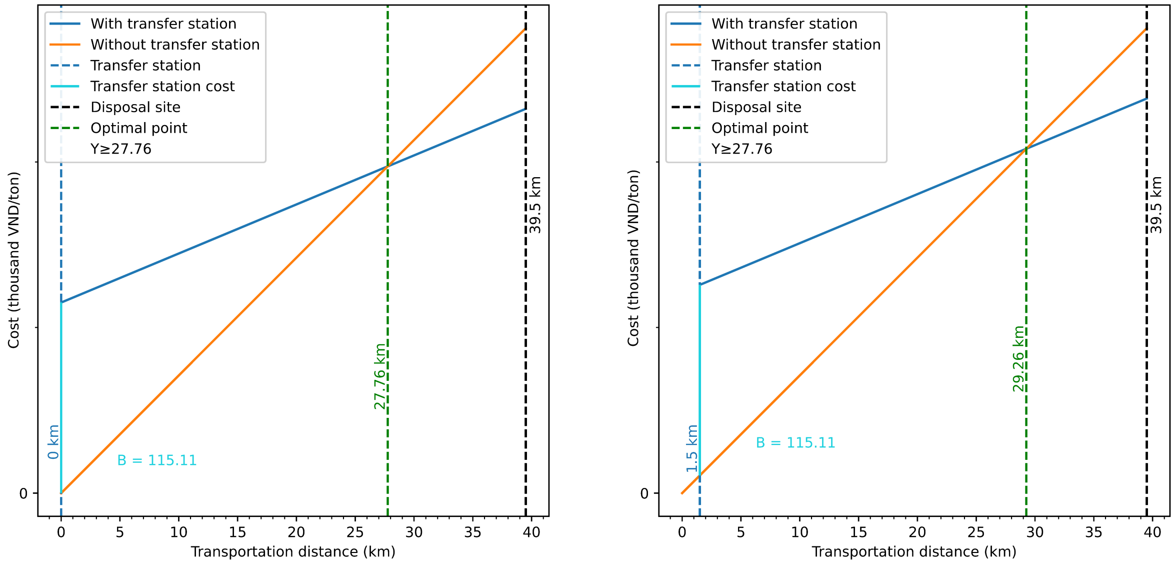
Fig. 2 illustrates the values of the distance-dependent correction factors together with the constrained linear regression line. According to the governmental pricing guidelines, the correction factors are published in a stepwise form, with each distance interval assigned a single fixed coefficient. This stepwise structure is standardized for the purpose of determining the reimbursable transportation cost paid by the State to service providers. However, for regression analysis, the study employs only the representative data points corresponding to each correction level. Converting the stepwise coefficients into discrete data points allows a clearer depiction of the actual variation in transportation cost, rather than reflecting costs only at broad distance intervals. Based on these data points, a linear regression function was constructed to represent a continuous relationship between the correction factor and transport distance, with Eq. (3):

$$K_{dc} = 0.031 \times L \tag{3}$$

where K_{dc} is the distance-dependent correction factor; L is the transport distance (km).

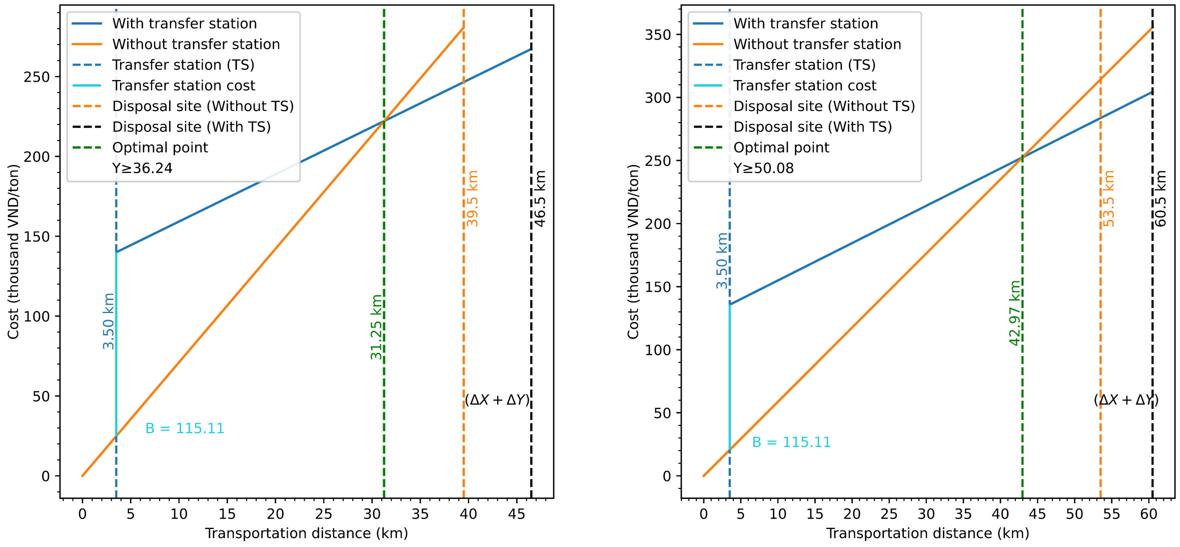
Previous studies commonly adopted the unit cost specified in Decision No. 30/2020/QĐ-UBND. However, the cost guidelines in this regulation provide only a single value for both large and small collection trucks. This approach leads to results that are inconsistent with the operational optimization principles of typical MSW transfer systems [24]. To address these limitations, government authorities have recently issued Decision No. 50/2025/QĐ-UBND of Hanoi City and Circular No. 36/2024/TT-BTNMT. These updated regulatory documents classify transportation vehicles into three major load categories: below 5 tonnes, from 5 to 10 tonnes, and above 10 tonnes. This improvement allows for more accurate calculations that better align with the operational optimization principles of MSW transport. Nevertheless, the new guidelines specify adjustment coefficients based on transport distance. From the 15th kilometer onward, the same coefficient is applied for every 5-km interval. This approach may cause the calculated results to deviate from the projected values and fail to clearly represent the relative optimization among scenarios. Therefore, this study applies the mean of the two boundary values to estimate a representative cost. Although this is an approximation method, it ensures consistency and comparability across all simulated scenarios.

According to the results calculated using the cost equation proposed by Ouano (1983), the breakpoint of $Y \geq 27.76$ km represents the threshold distance at which the use of TS becomes economically justified under the shortest-route condition. In other words, based on the calculated unit costs, when the distance from TS to the disposal site exceeds 27.76 km, TS option is more cost-effective than direct transportation from the end-of-route collection point to the disposal site. In cases where TS is not located along the shortest route, the detour distances for the Lam Du station were assumed as $\Delta X = 3.5$ km and $\Delta Y = 3.5$ km. TS option remains economically advantageous compared to direct hauling, applicable to both 7.5-tonne and 10.5-tonne compactor trucks.



(a) 7.5-tonne compactor truck and 11-tonne container truck

(b) 7.5-tonne compactor truck and 11-tonne container truck with the hypothetical TS



(c) 7.5-tonne compactor truck and 11-tonne container truck with the Lam Du TS

(d) 10.5-tonne compactor truck and 11-tonne container truck with the Lam Du TS

Figure 3. Results of the evaluation/determination of the optimal distance

Fig. 3 presents the results of determining the optimal distance for locating TS. Fig. 3(a) illustrates the relationship between the transportation costs of a 7.5-tonne compactor truck and an 11-tonne container or hooklift truck. In this case, the 7.5-tonne compactor truck transports waste directly from the collection point to the Nam Son Waste Treatment and Disposal Complex, whereas in the scenario with TS, an 11-tonne container truck is used for long-distance hauling. The cost curve of the 11-tonne container truck has a smaller slope, indicating a lower transportation cost over longer distances. However, because of the additional operational cost at TS, this cost curve starts at a higher level than that of direct transportation by an amount equivalent to $B = 115.106$ thousand VND/tonne. The results presented in Fig. 3(a) indicate that when the distance to the treatment facility exceeds 27.76 km, the option of using TS becomes more cost-effective in terms of transportation cost.

In the Vietnamese context, land allocated for TS is typically designated through urban planning and does not account for land cost. However, centrally located land parcels often possess higher economic development potential, which limits the feasibility of locating TS in city centers. Therefore, TS should be sited at a reasonable distance from collection areas. In this study, a hypothetical TS location was selected to evaluate the economic performance trend of the proposed option. The proposed site is classified as public service land and is not intended for commercial development. Therefore, land costs were not considered in the analysis. The hypothetical TS was placed 1.5 km from the end-of-route collection point and situated along the shortest route to the Nam Son Waste Treatment and Disposal Complex. The new TS should be designed in alignment with the city's urban development orientation and ensure convenient traffic accessibility. Fig. 3(b) presents the economic analysis results for the scenario with TS, where the distance from the end-of-route collection point to the station is 1.5 km. In this option, waste is collected and transported to TS by 7.5-ton compactor trucks, after which 11-ton container trucks are used to haul the waste from the station to the Nam Son Complex. The results indicate that the use of TS provides a significant economic advantage compared with direct hauling by 7.5-ton compactor trucks. Specifically, the transportation cost for direct hauling to the Nam Son Complex is 281 thousand VND per ton. Besides that, the scenario with the hypothetical TS reduces the cost to 238 thousand VND per ton, representing a decrease of approximately 15.3%.

Fig. 3(c) was developed to evaluate the efficiency of the Lam Du TS. In this case, the Lam Du station receives waste from 7.5-tonne compactor trucks and transfers it to 11-tonne container trucks for transportation to the Nam Son Waste Treatment and Disposal Complex. The Lam Du TS is not located along the shortest route from the end-of-route collection point to the Nam Son Waste Treatment Complex. Consequently, the transport distance through this station is longer than that of the direct-hauling option, with $\Delta X = 3.5$ km and $\Delta Y = 3.5$ km. The analysis results shown in Fig. 3(c) indicate that the use of the Lam Du TS reduces the transportation cost to 267 thousand VND/tonne. The transportation cost when using the Lam Du TS is 4.98% higher than that of the hypothetical TS.

Although the Lam Du TS demonstrates economic efficiency, its location is not situated along the shortest route to the Nam Son Waste Treatment and Disposal Complex. Therefore, it is necessary to examine whether increasing the load capacity of collection trucks for direct transportation could provide a more optimal solution. To address this issue, the study compares two scenarios: (i) direct transportation using 10.5-tonne compactor trucks and (ii) collection using compactor trucks followed by waste transfer at the Lam Du TS to 11-tonne container or hooklift trucks. Fig. 3(d) presents the analysis results for the direct transportation option using a 10.5-ton compactor truck, with a cost of 232,000 VND/ton at a transport distance of 39.5 km. This cost is theoretically representative because it does not include the collection route and is used only to compare cost-optimization trends. As a result, it does not reflect the actual operational distance. GPS data show that the average travel distance of compactor trucks when transporting waste directly to the treatment facility is approximately 53.5 km. At this distance, the direct transportation cost reaches 314 thousand VND/tonne, while

TS option costs 304 thousand VND/tonne. The results demonstrate that the use of TS remains the more cost-effective option under real operating conditions. In addition, increasing the load capacity of collection trucks also contributes to reducing the transportation cost of MSW.

3.2. Results of scenario analysis

a. Transportation distance and fuel consumption of the MSW transfer system

Table 2. Average daily transportation distance

Vehicle type	Scenario				
	BAU (Km/day)	SC1	SC2	SC3	SC4
Small truck/mini compactor truck	327.20		1077.05		
7.5-tonne compactor truck	1485.49			564.00	484.00
10.5-tonne compactor truck		1609.32			
11-tonne container/hooklift truck	354.99		1435.04	1435.04	1064.00
Total	2167.68	1609.32	2512.09	1999.04	1548.00

Table 2 presents the calculated average transportation distances for each scenario during a single operational day. The total travel distance of the system decreases substantially when shifting from the BAU to the hypothetical scenarios. Among them, Scenario SC2 exhibits the longest transportation distance, reaching 2512.09 km/day. Although TS is employed in this case, SC2 still records the highest total distance because the scenario utilizes small compactor trucks to transport waste from collection points to the Lam Du TS. The smaller truck capacity requires a greater number of trips to deliver the waste to TS compared with the use of large compactor trucks. Furthermore, the location of the Lam Du TS is not optimal in terms of its distance to the Nam Son Waste Treatment and Disposal Complex, which contributes to the overall increase in transportation distance. This pattern is clearly reflected in the data. Even though compactor trucks in SC2 operate only between collection points and the Lam Du TS, their average daily travel distance still reaches 1077.05 km, accounting for 42.8% of the total transportation distance in this scenario. The BAU scenario ranks second, with a total transportation distance of 2167.68 km/day. The total transport distance of SC1 is 1609.32 km/day, representing a significant reduction compared with the BAU and SC2 scenarios, but only a moderately lower value than that of SC3 (1999.04 km/day). Considering SC4, TS in this case is located along the shortest route, resulting in a reduction of the total daily transport distance to 1548 km. Consequently, SC4 represents the scenario with the shortest overall transportation distance among all cases.

Table 3 presents the calculated average daily diesel consumption for each operational scenario. The transport distance alone does not fully represent GHG emissions, as it also depends on the fuel consumption rate of each vehicle type. In terms of fuel use, SC1 consumes 1736.51 L/day and records the highest consumption among all scenarios. Although its total transport distance ranks only fourth, SC1 still reports the greatest fuel consumption because the 10.5-ton compactor truck used in this scenario has the highest fuel consumption coefficient. BAU exhibits the second-highest fuel consumption, reaching 1534.09 L/day. SC3 ranks third, with a consumption level of 1403.93 L/day. SC2 has the longest transport distance. however, its fuel consumption ranks only fourth, at 1075.11 L/day. This outcome is attributed to the predominant use of smaller trucks in SC2, which have lower fuel consumption coefficients and shorter collection routes located near TS. Finally, SC4 records a substantially low level of fuel consumption at 1097.13 L/day as a result of the optimized TS location.

Integrating digital data management systems and real-time material flow analysis can support adaptive transportation planning, optimize vehicle load utilization, and improve fuel-use efficiency [25].

Table 3. Average daily fuel consumption

Vehicle type	Fuel consumption rate (L/km)	Scenario				
		BAU (L/day)	SC1	SC2	SC3	SC4
Small truck/mini compactor truck	0.1418	46.39		152.69		
7.5-tonne compactor truck	0.8537	1268.22			481.51	413.21
10.5-tonne compactor truck	1.0790		1736.51			
11-tonne container/hooklift truck	0.6428	228.18		922.42	922.42	683.92
Total		1542.79	1736.51	1075.11	1403.93	1097.13

b. Assessment of greenhouse gas emissions and net climate impact

Fig. 4 illustrates the analysis results of black carbon (BC) emissions across the evaluated scenarios. BC is a SLCP that plays an important role in global climate change and is primarily produced from the incomplete combustion of fossil fuels. In this study, BC emissions originate from diesel engine operations during the collection and transportation of MSW. In the SC1 scenario, BC emissions are the highest among all cases. The second-highest BC emissions occur in BAU. All hypothetical scenarios that incorporate the use of TS show lower BC emissions compared with the BAU scenario. The third highest is SC3, followed by SC4 and SC2. Consistent with the trends observed in fuel consumption across scenarios, SC2 and SC4 also exhibit the lowest emission levels. Currently, newly invested collection and transportation vehicles are equipped with Euro 5 engines, which significantly reduce BC emissions compared with older models. Furthermore, this study and several recent ones recommend replacing fossil-fuel-powered vehicles with electric alternatives [26]. This transition can almost completely eliminate direct BC emissions during MSW transportation [26].

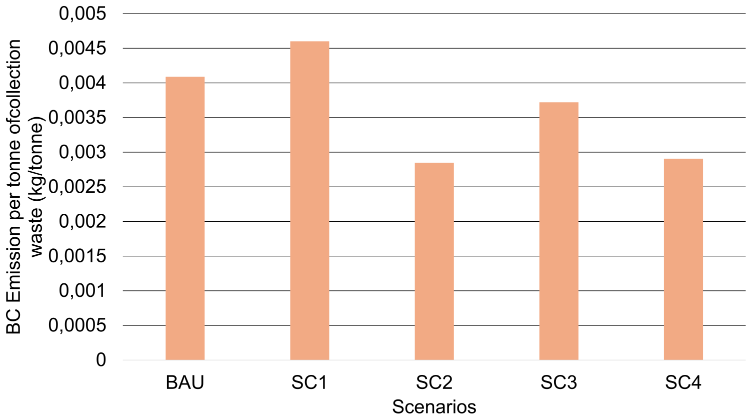


Figure 4. Black carbon emissions per tonne of collected MSW under different scenarios

Fig. 5 presents the analysis results of GHG emissions per tonne of MSW collected and transported. Among the emitted gases, CO_2 is the dominant component, while other GHG contribute only marginally and are considered negligible. CO_2 emissions are the primary outcome of MSW transportation activities, generated through the combustion of diesel fuel in vehicle engines [27]. Therefore, the level of CO_2 emissions directly reflects the fuel consumption pattern of each scenario.

The SC1 scenario exhibits the highest emission level, with approximately 31.42 kg GHG/tonne. Following the same trend observed in fuel consumption, scenarios BAU and SC3 show progressively lower emission levels, at 28.24 and 25.73 kg GHG/tonne, respectively. Finally, the two scenarios with the lowest emission levels are SC4 (20.18 kg GHG/tonne) and SC2 (19.78 kg GHG/tonne), each representing a reduction of more than 28% compared with the BAU scenario.

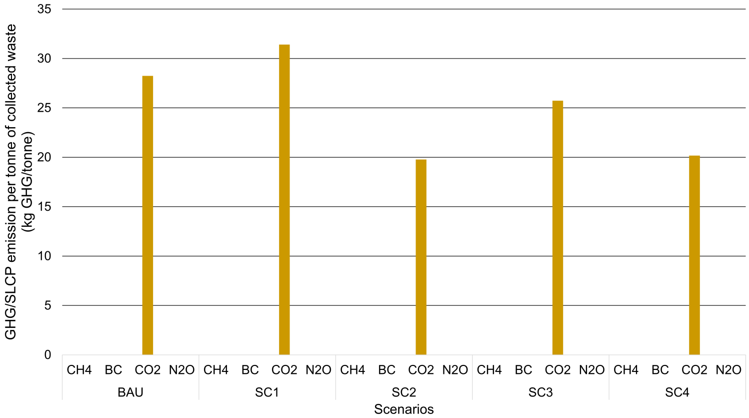


Figure 5. GHG and SLCP emissions per tonne of collected waste under different scenarios

Fig. 6 presents the results of the assessment of climate change impacts generated from the MSW transportation system. The climate impact was quantified by converting emissions of CO_2, CH_4, and N_2O into CO_2-equivalent using their respective 100-year Global Warming Potential (GWP-100) values. In this calculation, the EQT does not account for BC emissions. The scenario with the highest climate impact is SC1, with an emission level of 31.9 kg CO_2-eq/tonne. The simulation results indicate that the net climate impact decreases significantly across all scenarios that use TS compared with the BAU scenario. Specifically, total emissions are reduced from 28.67 kg CO_2-eq/tonne in the BAU scenario to 26.12 kg CO_2-eq/tonne in SC3, 20.48 kg CO_2-eq/tonne in SC4, and 20.08 kg CO_2-eq/tonne in SC2. SC2 achieves a relatively substantial reduction in emissions, primarily due to the use of small trucks with lower fuel consumption coefficients and operation within short collection routes located near TS. SC4 emerges as the most effective scenario for emission reduction when considering operational characteristics, corresponding to a 28.5% decrease compared with the BAU scenario. In addition, the hypothetical TS scenario (SC4) achieves a 21.5% reduction in GHG emission compared with scenarios using the Lam Du TS (SC3). This trend reflects the relationship between fuel consumption and GHG emissions, thereby illustrating their contribution to climate change. As EQT Version III incorporates updated emission factors, the resulting estimates may be comparatively lower than those reported in earlier studies using previous emission factors [28].

The study results show that GHG emissions from MSW collection and transportation activities in the study area are approximately 28.67 kg CO_2-eq/tonne under the BAU scenario. In this study, the BAU scenario was developed under the assumption that the entire vehicle fleet complies with the Euro 5 emission standard, thereby representing the lowest emission level that can be achieved under the current context. GHG emissions primarily originate from CO_2 released during fossil fuel combustion [27]. Currently, the MSW transfer system operates inefficiently, with transport distance and fuel consumption identified as the main contributors to GHG emissions. Therefore, optimizing transport routes and selecting appropriate vehicle transfer combinations are essential to reduce GHG emissions. The comparison among scenarios indicates that larger collection trucks achieve higher operational efficiency, mainly because they require fewer return trips to unload waste compared with

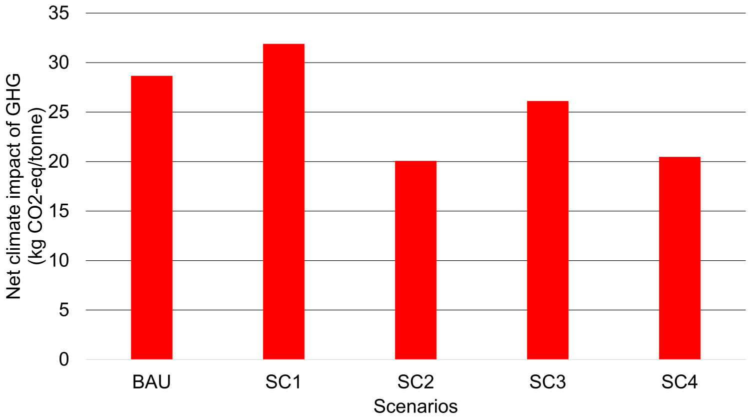


Figure 6. Net climate impact from waste transportation under different scenarios

smaller vehicles [28]. TS should be located on the shortest route connecting the collection areas and the disposal site, preferably as close to the collection areas as possible. Among the scenarios using trucks ranging from 7.5 to 11 tonnes, employing TS consistently proves to be more cost-effective than direct transportation. The hypothetical TS scenario was developed to show that when TS is located closer to the collection area, the transportation efficiency increases.

4. Conclusions

The findings of this study demonstrate that the use of TS combined with 11-tonne container/hooklift trucks is a more effective option than direct collection using 10.5-tonne compactor trucks to the Nam Son Waste Treatment and Disposal Complex. The current waste transfer operations remain inefficient, and utilizing TS for waste transshipment proves to be the optimal solution. The study developed and evaluated four different operational scenarios to quantify the relationship among transport distance, vehicle configuration, and GHG emissions. The analysis results identify the optimal configuration that simultaneously satisfies both cost and environmental performance criteria. This methodological framework can be applied to other cities and urban areas to optimize MSW transfer systems based on local operational conditions. Furthermore, the results provide important scientific evidence to support planning and decision-making for waste transfer infrastructure investment, while assisting public service enterprises in reducing emissions toward the goal of net-zero emissions in the MSW management sector.

However, this study has several limitations. First, input parameters such as fuel consumption, emission factors, and operational costs were mainly derived from average values and secondary data sources, which may introduce certain discrepancies compared to actual operating conditions. Second, although the regulatory authorities have issued separate cost norms and unit prices for each vehicle type, the load categories and distance-based adjustment coefficients are still defined within relatively broad ranges. These coefficients should be further refined for specific operational conditions to improve the accuracy of future assessments. Third, the study area was limited to a central district of Hanoi, and thus does not represent the total emissions of the entire city. Given the larger operational scale of the city, the actual emissions are expected to be higher than those estimated in this study. In future research, it is recommended to expand the study scope to more accurately assess the emission reduction potential across the entire Hanoi metropolitan area. Future studies should also develop and evaluate scenarios incorporating electric or clean-fuel vehicles to reduce direct emissions, particularly SLCP such as BC. Expanding research in these directions will help improve the assessment model and increase the reliability of the results. Consequently, the outcomes of this study can also contribute to the development of a circular economy-oriented MSW management system.

Acknowledgment

The authors gratefully acknowledge the financial support from Hanoi University of Civil Engineering for the research project entitled "Assessment of Greenhouse Gas Emissions from Municipal Solid Waste Collection and Transfer Systems in Major Cities and Proposed Mitigation Solutions", research project code: 08-2025/KHXD.

References

[1] IPCC (2023). *Synthesis Report of the IPCC Sixth Assessment Report (AR6)*. IPCC, Switzerland.

[2] United Nations Environment Programme, International Solid Waste Association (2024). *Global Waste Management Outlook 2024: Beyond an Age of Waste - Turning Rubbish into a Resource*. UNEP.

[3] Filonchyk, M., Peterson, M. P., Zhang, L., Hurynovich, V., He, Y. (2024). Greenhouse gases emissions and global climate change: Examining the influence of CO2, CH4, and N2O. *Science of The Total Environment*, 935:173359.

[4] IPCC (2014). *Climate Change 2014 Synthesis Report Summary Chapter for Policymakers*. IPCC, Switzerland.

[5] Li, Y., Zhang, S., Liu, C. (2022). Research on Greenhouse Gas Emission Characteristics and Emission Mitigation Potential of Municipal Solid Waste Treatment in Beijing. *Sustainability*, 14(14):8398.

[6] United States Environmental Protection Agency (2024). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*. US EPA. Accessed on 25/10/2025.

[7] United States Environmental Protection Agency. *Greenhouse Gas Equivalencies Calculator*. US EPA. Accessed on 25/10/2025.

[8] European Environment Agency (2016). *EMEP/EEA air pollutant emission inventory guidebook - 2016*. European Union.

[9] Syeda, A. B., Jadoon, A., Chaudhry, M. N. (2017). Life cycle assessment modelling of greenhouse gas emissions from existing and proposed municipal solid waste management system of Lahore, Pakistan. *Sustainability*, 9(12):2242.

[10] Liao, N., Lü, F., Zhang, H., He, P. (2024). Optimizing the greenhouse gas emissions of waste transfer and transport: An integration of life cycle assessment and vehicle routing problem. *Waste Management*, 189: 314–324.

[11] Dinh, P. V., Giang, H. M., Notodarmojo, P. A., Giang, N. H. (2025). Utilizing Unmanned Aerial Vehicles as a Low-Cost Surveying Method for Landfill Management: A Case Study at Quang Loi. *Journal of Science and Technology in Civil Engineering*, 19(4):46–57.

[12] Quilcaille, Y., Gudmundsson, L., Schumacher, D. L., Gasser, T., Heede, R., Heri, C., Lejeune, Q., Nath, S., Naveau, P., Thiery, W., Schleussner, C.-F., Seneviratne, S. I. (2025). Systematic attribution of heatwaves to the emissions of carbon majors. *Nature*, 645(8080):392–398.

[13] Prime Minister of the Socialist Republic of Vietnam (2022). *Approving the National Action Plan on Circular Economy Implementation for the period 2022–2030*. Decision No. 896/QĐ-TTg.

[14] Maison Office. *Hoan Kiem District: Area & administrative information of wards*. Maison Office. Accessed on 25/10/2025.

[15] Ngo, T. L. P. (2023). *Municipal Solid Waste in Hanoi City, Vietnam: Movements to Development of Circular Economy and Climate Change Adaptation*. URENCO.

[16] Ouano, E. A. R. (1983). Hauling distance and transfer station location. *Journal of Environmental Engineering*, 109(6):1429.

[17] People's Committee of Hanoi City (2025). *Labor norms and unit prices for solid waste collection, transportation, and treatment services in Hanoi City*. Decision No. 50/2025/QĐ-UBND.

[18] Ministry of Natural Resources and Environment (2024). *Prescribing technical norms, cost norms, and fuel consumption for collection, transport, and treatment of municipal solid waste*. Circular No. 36/2024/TT-BTNMT.

[19] Ministry of Labour - Invalids and Social Affairs (2019). *Salary classification and wage scales for public service units*. Circular No. 17/2019/TT-BLĐTBXH.

[20] Government of Vietnam (2004). *Salary regimes for cadres, civil servants, public employees, and armed forces personnel*. Decree No. 204/2004/NĐ-CP.

[21] Diaz, R., Warith, M. (2006). Life-cycle assessment of municipal solid wastes: Development of the WASTED model. *Waste Management*, 26(8):886–901.

[22] Ministry of Finance (2023). *Guiding the classification of tangible fixed assets and management of depreciation in administrative and public service units*. Circular No. 23/2023/TT-BTC.

[23] IGES. *Emission Quantification Tool (EQT): A Pathway to Climate-Friendly Waste Solutions*. IGES. Accessed on 25/10/2025.

[24] Hoang, G. M., Ha, H. T. T., Le, N. T. L., Toan, N. D. (2024). Evaluation of municipal waste collection performance using operational data. *Global Journal of Environmental Science and Management*, 10(1).

[25] Khanh, T. B., Giang, H. M., Anh, D. H., Nga, T. T. V. (2025). Leveraging Material Flow Analysis (MFA) as a Tool for Hazardous Waste Data Management in Viet Nam. *Journal of Science and Technology in Civil Engineering*, 19(4V):74–84.

[26] Moreno-Solaz, H., Artacho-Ramírez, M.-Á., Aragonés-Beltrán, P., Cloquell-Ballester, V.-A. (2023). Sustainable selection of waste collection trucks considering feasible future scenarios by applying the stratified best and worst method. *Heliyon*, 9(4):e15481.

[27] Fruergaard, T., Astrup, T., Ekvall, T. (2009). Energy use and recovery in waste management and implications for accounting of greenhouse gases and global warming contributions. *Waste Management and Research*, 27(8):724–737.

[28] Eisted, R., Larsen, A. W., Christensen, T. H. (2009). Collection, transfer and transport of waste: Accounting of greenhouse gases and global warming contribution. *Waste Management and Research*, 27(8): 738–745.