Journal of Allied Health Disciplines 2025, 1(2), 1-9

Material Flow Analysis for Sustainable Construction: A Case Study of Carbon Emissions in Northern Malaysia

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ABSTRACT

The construction industry supports Malaysia's economy but also generates substantial waste and carbon emissions, posing risks to the environment and public health. This study applied Material Flow Analysis (MFA), integrated with carbon foot printing, to quantify material waste and carbon emissions from transportation and energy use in two large-scale projects in northern Malaysia. Data on material inputs, waste outputs, transport distances, and energy consumption were collected over a 12-month period. The MFA revealed that approximately 4–5% of total input materials were wasted, with bricks representing the largest material loss. Brick waste was also the greatest contributor to transportation-related CO_2 emissions, reflected in the highest carbon footprint among all waste materials. In contrast, bulldozers accounted for the greatest energy-related emissions, despite greater overall energy consumption in electricity use. The findings highlight the need for brick waste reduction, optimised logistics, and the adoption of low-carbon fuels as key strategies to improve sustainability and mitigate environmental and health impacts in the construction sector.

Keywords: carbon emission, carbon footprint, construction waste, environmental health, Material Flow Analysis (MFA), sustainable construction

1.0 INTRODUCTION

The construction industry is rapidly expanding due to rising living standards, increasing demand for infrastructure, and natural population growth, which tends to rise with higher income levels [1]. In Malaysia, the construction industry is one of the main sectors contributing to national economy growth. According to Malaysia's Construction Industry Development Board (CIDB), the construction industry achieved a growth rate of 5% in 2024, with the total value of completed construction projects reaching RM158.8 billion [2]. Over the past five years, Malaysia has completed numerous projects, including high-rise commercial buildings, highways, motorways, tunnels, bridges, industrial facilities, schools, hospitals, power plants, the mass rapid transit (MRT) rail system, and housing developments. The country has also undertaken several construction projects in the tourism and manufacturing sectors [2].

However, the rapid increase in construction activities has resulted in the generation of massive amounts of construction waste [3]. Construction waste is not only a critical issue in Malaysia but also a global concern, affecting both developing and industrialised countries such as China, the United States, Singapore, and Japan [3]. For example, China generates approximately 1,130 million tonnes of construction waste annually, compared with 534 million tonnes in the United Sates and 8 million tonnes in Malaysia [3,4]. Construction waste differs from municipal waste in that it is generated during the renovation, construction, modification, and demolition of roads, buildings, and other constructed structures [5]. It includes materials such as concrete, bricks, tiles, ceramic, metals, aggregates, wood, direct and indirect water, packaging materials, and other demolition by-products. Although there are possibilities for reuse, recycling, and waste minimisation, a significant amount of construction waste continues to be generated [6].

In addition, growing demand for construction increases energy consumption, water usage, and carbon emissions simultaneously, due to the embodied energy and CO_2 emissions associated with construction materials [5]. While the construction sector plays a vital role in national economic development, its activities contribute substantially to greenhouse gas emissions, leading to serious consequences such as global warming, heat-related illness, and respiratory diseases.

There are two main types of carbon emissions in the construction industry: direct and indirect. Direct carbon emissions arise from on-site operations, such as construction, maintenance, and demolition, whereas indirect carbon emissions result

Article Information

Received: 21 August 2025
Accepted for publication: 4 October 2025
Published: 30 November 2025

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from the supply of products and services supporting construction, including upstream processes such as brick and cement manufacturing [7]. Both types of carbon emissions are important when formulating strategies to reduce emissions at different stages of project development [8]. Direct emissions are essential to examine when identifying reduction options during the construction phase, while indirect emissions should be considered when assessing mitigation opportunities during the design and planning stages [7].

For developing nations, reducing emission is essential to achieving sustainable economic and environmental development [7]. In Malaysia, however, there are currently no legal or economic mechanisms in place to assist construction professionals in reducing waste generated and energy consumption, which would in turn help lower carbon emission [9]. A thorough understanding of the magnitude of construction waste generation and the corresponding carbon emissions across various construction phases is important for the formulation and implementation of targeted strategies towards national sustainability goals.

Hence, this study aims to identify quantity of construction waste generated and carbon emission from transportation and energy use from two construction sites in the northern Malaysia. Subsequently, overall amount of the construction waste generated and carbon footprint during the construction stages was identified using Material Flow Analysis (MFA). MFA is crucial in understanding total amount of waste generated from material used in the beginning until completion of a construction project. Therefore, it will help in managing the waste properly without causing any adverse impacts to the environment.

2.0 MATERIAL AND METHODS

2.1 Study Design and Study Location

The quantitative cross-sectional study design was applied in this study, whereby data for from two construction sites were collected simultaneously over a 12-month period. Two construction projects, namely Construction Site A (CS A) and Construction Site B (CS B), located in the northern region of Malaysia, were selected for this study. CS A is a project involving the construction of office buildings, consisting of five administrative blocks and several facility blocks, including parking lots, with a total built-up area of 69,176.6m². On the other hands, CS B is an infrastructure development project comprising sewage treatment plants, administrative office and facility buildings, with a total built-up area of 28,740m².

2.2 Data Collection

2.2.3 Quantification of Construction Waste Materials and Carbon Emissions from Waste Transportation

The major types of construction materials used at both construction sites were determined from Bill of Quantities (BOQ) documents prepared by the sites' quantity surveyors. Five major construction materials were selected based on their highest volume of consumption. Details information on the amount of each material used is presented in Table 1.

Subsequently, the total weight of the selected construction waste materials was obtained from the payload measurements of the trucks that transported the waste to the designated landfill sites. The estimation of carbon dioxide (CO_2) emissions from the transportation of construction waste from

Table 1: Types of construction materials per unit, weight and volume and construction materials used at CS A and CS B.

Construction Material	Construction Site	Construction materials per unit, weight and volume			Construction materials used		
		(A) Unit (bag/pallet/ m³)	(B) Weight (kg)	(C) Volume (m³)	(A) Unit (bag/pallet/ m³)	(B) Weight (kg)	(C) Volume (m³)
Cement	CS A	1 Bag	50	0.034	3,348	167,400	113.832
	CS B	1 Bag	50	0.034	1,231	61,550	41.854
Sand	CS A	1 Bag	50	0.031	13,206	660,300	409.386
	CS B	1 Bag	50	0.031	5,638	281,900	174.778
Brick	CS A	1 Pallet	1554	0.132	5,766	8,960,364	761.112
	CS B	1 Pallet	1451	0.132	2,418	3,508,528	319.176
Steel	CS A	1 Pallet	37	0.132	5,952	220,224	1,976.064
	CS B	1 Pallet	41	0.132	2,496	102,336	828.672
Timber	CS A	1 Pallet	50	1.324	6,603	330,150	8,742.372
	CS B	1 Pallet	50	1.324	2,781	139,050	3,682.044

Note: Unit per pack for each material (A), material's weight per pack (B) and material's volume per pack (C).

the construction sites to the landfill is a crucial component of the overall carbon assessment. Therefore, the quantification of CO_2 emissions was calculated using the Transportation Calculation Method, as shown in Equation 1 [10, 11]. The distance from each construction site to the landfill was estimated using Google Maps.

Transportation Calculation Method ….(Equation 1)
Amount of CO_2 emission ($kgCO_2$) =
$Amount\ of\ waste\ (kg)\ x\ Distance\ to\ landfill\ (km)\ x\ EF$
EF - Emission factor of CO_2 released during transportation [11].

2.2.4 Quantification of Carbon Emission from Energy Consumption

Carbon dioxide (CO_2) emissions from diesel-powered machinery and electricity consumption during construction activities were quantified using Equation 2. This calculation requires two parameters, namely activity data (AD) and the emission factor (EF). The AD represents the magnitude of a specific activity during the construction process, such as the amount of electricity or diesel consumed within a given period. The EF represents the mass of greenhouse gases emitted per unit of AD.

Carbon emission = Activity data (AD) x Emission Factor (EF) ….Equation (2)

Emission conversion factors established in the Malaysian Carbon Reduction and Environmental Sustainability Tool (MyCREST) were used to calculate the emissions associated with energy use [12].

2.2 Data Analysis

Data analysis was performed after all required data had been fully collected from both construction sites. All data were analysed using Material Flow Analysis (MFA). MFA was used as a tool to measure the amount of construction waste produced during the construction stage. The MFA was illustrated by Sankey diagrams, which depict the overall material and energy flows, including sources, energy and the raw materials. These diagrams link the sources and flow pathways to the final material sinks. These methods enabled the identification and quantification of material flows and waste generation throughout the construction process.

3.0 RESULTS

3.1 Amount of Waste Generated at CS A and CS B.

The amount of waste generated at both construction sites is shown in Table 2. Based on the table, there was a difference in the amount of waste generated at CS A and CS B. Brick waste was the most abundant at both sites, amounting to 358,414 kg at CS A and 140,341 kg at CS B. This was followed by sand waste, with 66,030 kg recorded at CS A and 27,690 kg at CS B. Cement waste was the least generated material, with 8,370 kg at CS A and 3,120 kg at CS B.

3.2 Carbon Emissions from Construction Waste Transportation

All construction waste was transported from the sites to designated landfill facilities for disposal. The distance between each construction site and its respective landfill was used to calculate the total amount of carbon dioxide (CO_2) emissions. The average distance recorded was 5 km for CS A and 17 km for CS B.

The results of total amount of carbon emissions generated from waste transportation are presented in Figure 1. In general, the transportation of waste from CS B to the landfill produced higher CO_2 emissions compared to CS A. As shown in Figure 1, brick waste transportation contributed the highest carbon emissions at both construction sites, with 34,229 kg from CS A and 45,569 kg CO_2 from CS B. Sand waste was the second highest contributor, producing 6306 kg CO_2 at CS A and 8,991 kg CO_2 at CS B. By contrast, cement and steel waste transportation generated the lowest CO_2 emissions, with less than 2,000 kg CO_2 recorded for the stated waste types.

Table 2: Types of construction materials, total weight of materials used, and wasted in kg at CS A and CS B.

Types of construction material	Construction Site A (CS A)		Construction Site B (CS B)	
	Total weight (used) (kg)	Total weight (wasted) (kg)	Total weight (used) (kg)	Total weight (wasted) (kg)
Cement	167,400	8,370	62,400	3,120
Sand	660,300	66,030	276,900	27,690
Brick	8,960,364	358,414	3,508,528	140,341
Steel	220,224	11,011	102,336	5,116
Timber	330,150	33,015	138,450	13,845

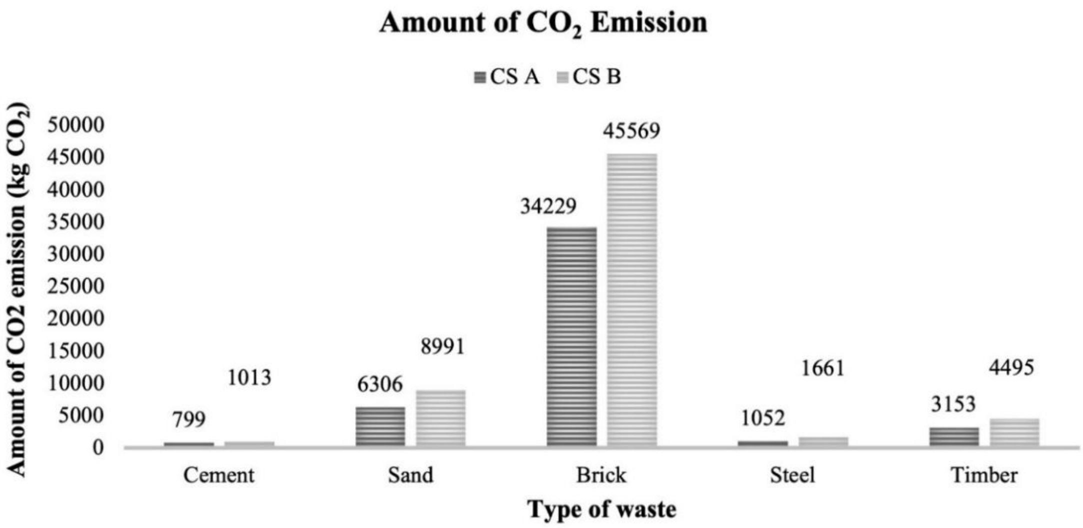

Figure 1: Amount of carbon dioxide emissions from material waste at CS A and CS B.

Table 3: Types of energy used and sources of consumption – CS A and CS B.

Type of Energy	Source of consumption	Item	Quantity
CS A	Construction machinery/equipment	Piling machine	1
Diesel		Excavator	4
		Mobile crane	2
		Tower crane	2
		Bulldozer	4
	Vehicle/transportation	Heavy truck	4
Electricity		Truck	3
	On-site electricity	Based on meter	-
CS B	Construction machinery/equipment	Piling machine	1
Diesel		Excavator	2
		Mobile crane	1
		Tower crane	1
		Bulldozer	2
	Vehicle/transportation	Heavy truck	2
Electricity		Truck	3
	On-site electricity	Based on meter	-

3.4 Types of Energy Used and Amount of Energy Consumption in Construction Projects

The primary sources of energy consumption at CS A and CS B were assessed based on two types of energy: diesel fuel used by diesel-powered machinery and electricity (Table 3). These energy sources were mainly utilised for construction machinery and equipment, transportation and on-site activities.

Based on Table 4, the piling machine recorded the highest diesel consumption, using 45 L/hour at both CS A and CS B for 8 hours per day, but operating for a maximum of only 7 days/year. Despite having the highest hourly diesel usage, the piling machine operated the least frequently since it was used only during the early stage of construction for piling works. On the other hand, the tower crane consumed the least diesel fuel, at 16 L/hour, and operated for 34 days per year at CS A and 15 days per year at CS B.

Among all machinery, heavy trucks were the most frequently used at both sites, consuming an average of 45.64 L/hour. Besides heavy truck, bulldozers were also frequently employed during construction activities, with diesel consumption of 36.62 L/hour for both sites.

On-site electricity consumption for CS A was 93.12 kWh per hour, while CS B consumed 67.22 kWh per hour. Electricity was supplied for 12 hours per day to support various construction activities and remains accessible for 266 days per year at CS A and 272 days per year at CS B. The annual energy consumption was calculated by multiplying parameters (A), (B) and (C).

Table 4: Diesel and electricity consumption at CS A and CS B.

Construction site	Types of energy	Items	Quantity	(A) Consumption (L/hour)	(B) Duration (hour/day)	(C) Total days (day/year)
CS A	Diesel (L)	Piling machine	1	45	8	5
		Excavator	4	33	8	65
		Mobile crane	2	20.54	8	89
		Tower crane	2	16	8	34
		Bulldozer	4	36.62	8	89
		Heavy truck	4	27.55	8	112
		Truck	4	18.09	8	104
	Electricity (kWh)	On-site electricity used	Based on meter	52.22	12	266
CS B	Diesel (L)	Piling machine	1	45	8	7
		Excavator	2	33	8	34
		Mobile crane	1	20.54	8	20
		Tower crane	1	16	8	15
		Bulldozer	2	36.62	8	91
		Heavy truck	2	27.55	8	109
		Truck	3	18.09	8	118
	Electricity (kWh)	On-site electricity used	Based on meter	37.22	12	272

Note: Energy consumption per hour (A), duration of energy used per day (B), and total days of energy being used in one year (C).

The quantity multiplied was then converted into megajoules (MJ) to determine the total energy consumption of each item over a 12-month period, as presented in Figure 2.

According to the results, the bulldozer utilized the highest total energy at both CS A and CS B. Bulldozers are large machines used for pushing, digging, excavating, and levelling materials; therefore, they consume substantial amounts of energy per operating hour. They operated between 89 to 91 days per year at both CS A and CS B. In contrast, piling machine consumed the least total energy, with 6,480 MJ at CS A and 9,072 MJ at CS B, due to its limited operating days despite high hourly consumption Similarly, the tower crane consumed the least energy at CS B, with only 6,912 MJ recorded.

3.5 Total Carbon Emissions from Diesel-powered Machinery and Electricity Consumption

Figure 3 illustrates the total carbon dioxide emissions resulting from energy consumption in machinery, equipment, transportation, and building operations that used diesel fuel and electricity. Overall, CS A produced higher total carbon emissions from energy consumption compared to CS B. The bulldozer was the largest contributor to total carbon emissions at both sites, producing 244, 846 and 125,173 kg CO_2^{-e}/unit for CS B and CS A, respectively. In contrast, the piling machine contributed lowest total carbon emissions, with 4,221 kg CO_2^{-e}/unit for CS B and 5,910 kg CO_2^{-e}/unit for CS A.

3.3 Material Flow Analysis (MFA) on Material Waste Generated

Figure 4 presents the Sankey diagram depicting the material flows for CS A and CS B, covering all five materials: sand, brick, steel, timber and cement (in kilograms). The diagram integrates both the total of materials used and the quantities of waste generated throughout the construction process.

The total materials represent the total amount of materials used, and materials wasted for the project. The materials used is the exact amount of the total materials including brick, cement, sand, steel and timber. The material waste was calculated by subtracting a specific percentage of waste. Each materials have different percentage of waste. Based on the Bill of Quantities (BOQ), the wastage rates were 4% for brick, 5% for cement and steel, and 10% for sand and timber. The Sankey diagram shows that there is 5% of the total materials used were wasted across both construction sites. Among all materials, brick waste exhibited the highest contribution, indicating its role as the major carbon footprint source, whereas cement waste contributed the least.

4.0 DISCUSSION

This study applied a Material Flow Analysis (MFA) approach to quantify construction waste generated from total material usage and associated carbon emissions from two large-scale projects in northern Malaysia. The results clearly show that brick waste was the most dominant contributor to overall waste and carbon emissions at both construction sites. For CS A and CS B, brick waste accounted for 358,414 kg and 140,341 kg, respectively (Table 1), leading to the highest carbon footprint during waste transportation (34,229 and 45,569 kg CO_2), as shown in Figure 1. This finding is consistent with recent studies reporting that brick manufacturing and use contribute substantially to environmental pollution and carbon emissions due to energy-intensive production and heavy material handling [13,14]. The results also revealed that cement waste was the least generated (<9,000 kg in CS A and <4,000 kg in CS B), which is expected since cement is usually prepared in measured quantities on-site. However, despite lower waste volumes, cement remains a critical material in the carbon accounting framework. Global evidence indicates that cement production continues to be a major source of carbon emissions and a growing challenge for sustainable construction [15]. This emphasises that reduction strategies should address not only waste minimisation but also consider upstream emissions from cement manufacturing.

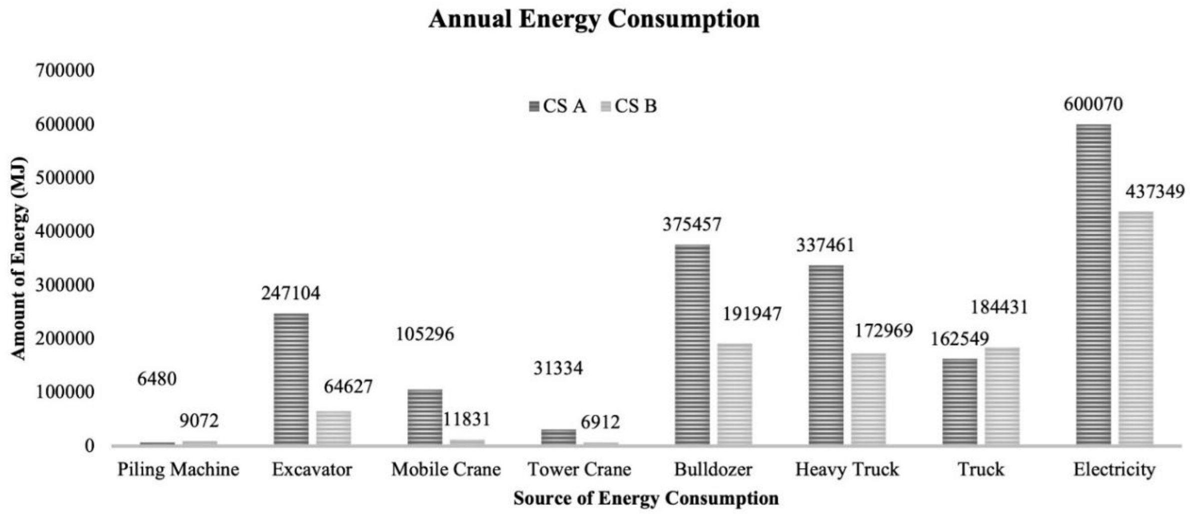

Figure 2: Annual energy consumption from diesel-powered machinery and electricity.

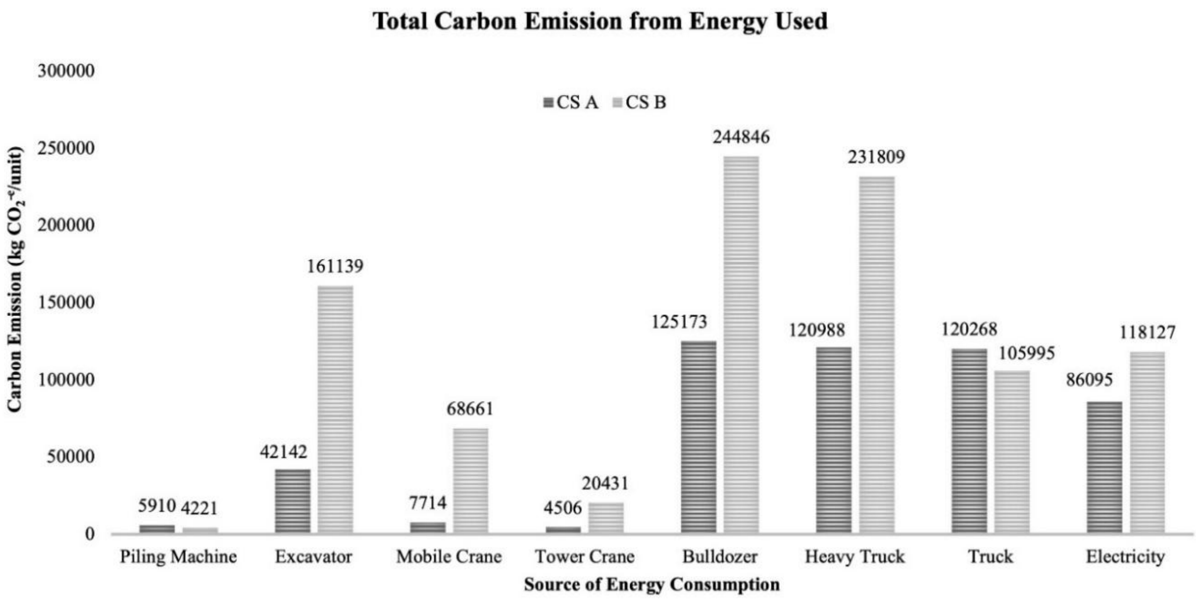

Figure 3: Total carbon emissions from energy used.

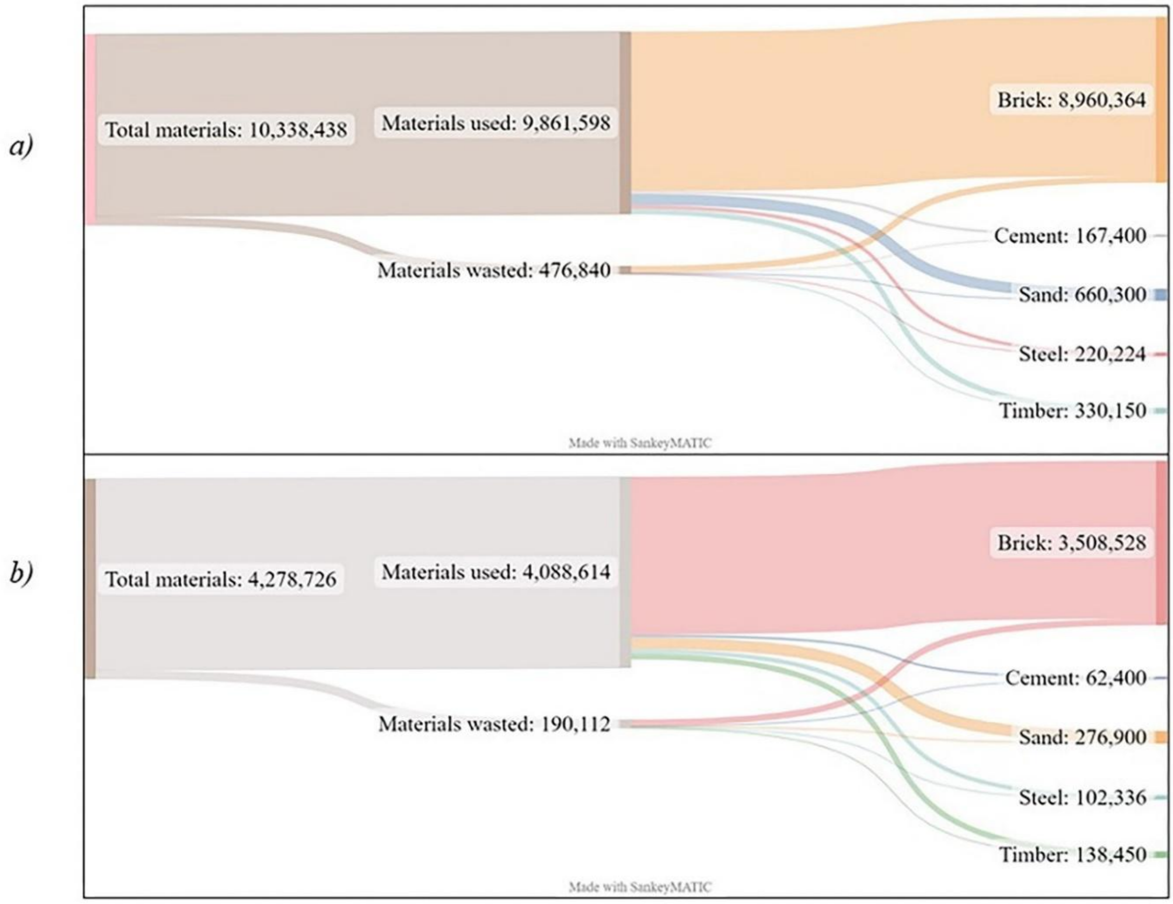

Figure 4: Sankey diagram for flow of materials used and material wasted in kg, (a) CS A and (b) CS B.

In terms of transportation-related emissions, CS B generated higher CO_2 emissions despite producing less total waste compared with CS A (Figure 1). This difference was due to the longer average hauling distance (17 km for CS B vs. 5 km for CS A). This result underscores the significant role that logistics play in the carbon footprint of construction waste. Optimising haulage distances, deploying more efficient fleets, or adopting localised recycling practices could substantially lower transportation-related emissions, consistent with recent findings on spatial MFA and carbon footprints of waste systems [15, 16].

Regarding energy consumption, diesel-powered equipment contributed more carbon emissions than electricity use (Figure 3). Among all machinery, bulldozers emerged as the largest contributor to carbon emissions at both sites, producing 244,846 kg CO_2-e/unit at CS B and 125,173 kg CO_2-e/unit at CS A. This reflects the heavy-duty nature and prolonged operating hours of bulldozers compared with other equipment such as piling machines or tower cranes. A recent study also highlighted that on-site diesel-powered equipment is a major contributor to construction-related emissions, surpassing electricity due to both fuel intensity and emission factors [17].

The MFA Sankey diagrams presented in Figure 4 further support these findings by visualising the flow of materials and their wastage. In CS A, a total of 10,338,438 kg of materials were supplied, of which 476,840 kg (~4.6%) were wasted, while CS B consumed 4,278,726 kg with 190,112 kg (~4.4%) wasted. Despite the difference in project scale, both sites displayed similar waste percentages, indicating systemic inefficiencies in material management. In both projects, bricks overwhelmingly dominated the waste stream, accounting for nearly 9 million kg in CS A and 3.5 million kg in CS B. In contrast, waste from cement, steel, and timber was comparatively minimal. This suggests that brick handling, cutting, and storage practices are the primary hotspots of inefficiency, while steel and timber are managed more effectively. Since bricks are also the heaviest material, their wastage not only increases landfill loads but also elevates transportation-related emissions. Similar waste patterns, particularly in brick use, have been reported in recent MFA-based assessments for construction waste in China, highlighting that this challenge is common across construction projects and requires targeted intervention [18].

The integration of MFA with carbon foot printing in this study provided a comprehensive understanding of both material inefficiencies and their environmental consequences. MFA quantified the flows of construction materials and revealed that approximately 4–5% of inputs were consistently wasted across both sites, with bricks representing the largest loss. It was evident that brick waste not only dominated material loss but also produced the highest transportation-related CO_2 emissions, reflecting the highest carbon footprint among all waste materials. This demonstrates how MFA can serve as a valuable tool for carbon footprint determination, enabling the translation of material flows into climate impacts within construction waste management for sustainable development [18].

Overall, the findings demonstrate that both material waste particularly brick waste and diesel consumption are key hotspots of carbon emissions in construction projects. Addressing these issues requires a dual strategy: improving material efficiency and recycling practices to reduce waste generation and transportation loads and adopting low-carbon technologies and alternative fuels to reduce diesel dependency. Such measures would align with Malaysia's MyCREST framework and global calls for carbon reduction in the building sector, thereby reducing air pollution and its associated public health impacts [15, 19, 20].

5.0 CONCLUSION

This study employed Material Flow Analysis (MFA) to assess construction waste and carbon emissions at two large-scale projects in northern Malaysia. The findings showed that brick waste was the major contributor to material losses and emissions, while cement waste, though smaller in volume, remained highly carbon intensive. Transportation-related emissions were greater at CS B due to longer hauling distances, and diesel-powered machinery, particularly bulldozers, produced the highest energy-related emissions.

MFA revealed that approximately 4–5% of input materials were wasted across both sites, reflecting systemic inefficiencies rather than project-specific issues. By visualising material flows, MFA effectively identified critical hotspots particularly bricks waste which not only increases landfill and transport burdens but also contributes to broader health risks associated with carbon emissions and air pollution.

Integrating MFA into construction practice offers a robust pathway to improving resource efficiency, reducing emissions, and promoting sustainable and health-conscious development in Malaysia.

ACKNOWLEDGEMENTS

The authors would like to thank the construction sites involved in this study for their cooperation and assistance in completing the research.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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