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Carbon Footprint Evaluation of Hazardous Waste Based Solid Fuel: Application in a Cement Kiln

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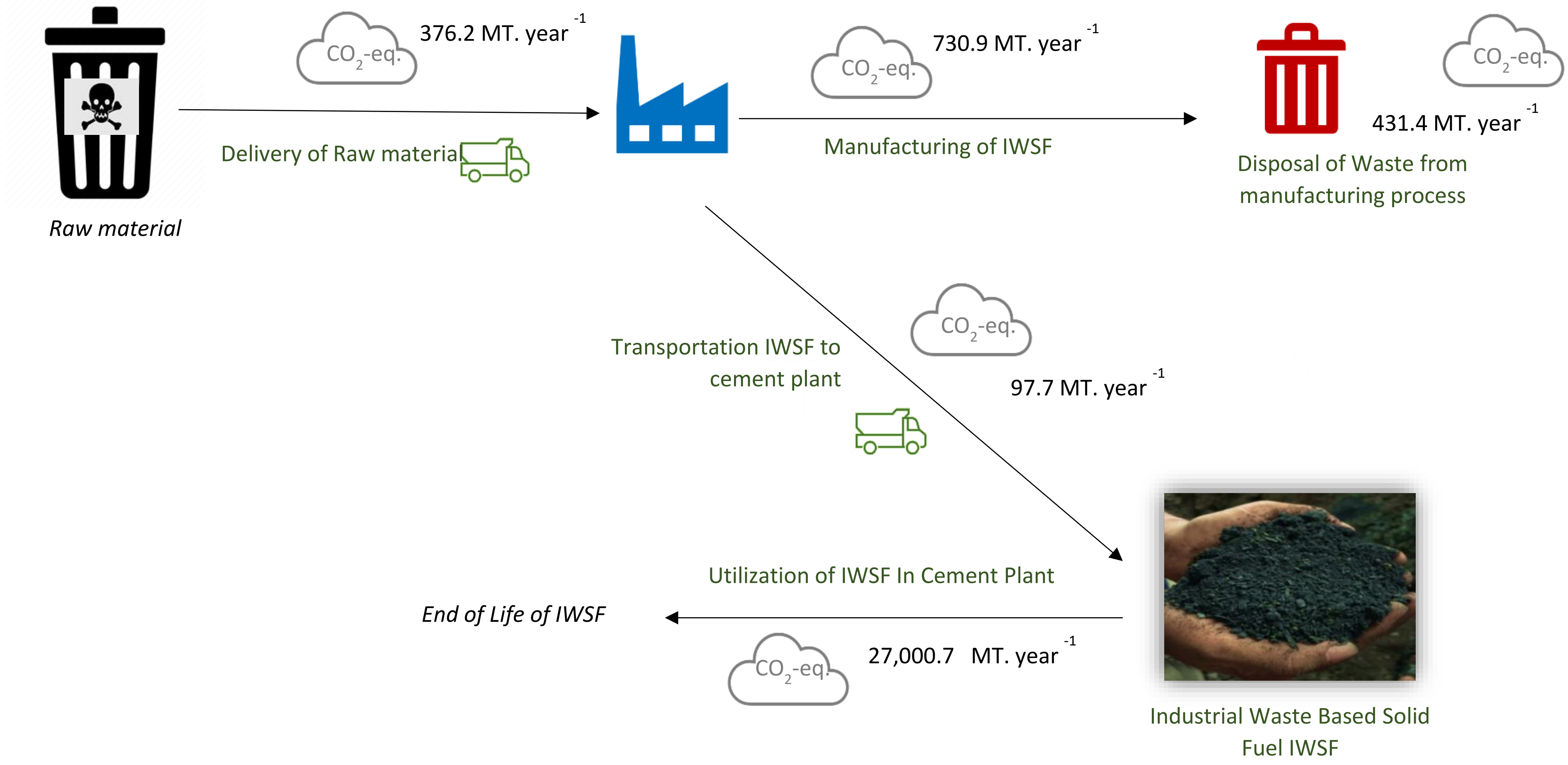
Abstract

This study aimed to evaluate industrial wastes-based solid fuel (IWSF) carbon footprint from the boundary of the cradle-to-grave life cycle. It includes emissions released from the transportation, manufacturing of IWSF, waste disposal, utilization of IWSF in the cement manufacturing plant, and end of life of IWSF. The quantification of total IWSF carbon footprint measures greenhouse gas emissions, carbon dioxide, nitrous oxide, and methane and is expressed as carbon dioxide equivalent (CO_2-eq). The CO_2-eq emission factors are calculated based on Intergovernmental Panel on Climate Change (IPCC) guideline, and the information used in this study is obtained from the actual operation. The study confirmed that the total carbon footprint of IWSF is approximately 0.17 kg CO2-eq. MJ-1 energy generated. The results show that the utilization of IWSF at a cement manufacturing plant is the key contributor to carbon footprint, contributing to 94.3% of the total percentage, with a quantitative value of 27,000.7 MT CO_2-eq per year IWSF manufacturing stage with 2.6 %. Subsequently, CO_2-eq emission reduction initiatives have been implemented by the IWSF manufacturer, able to reduce approximately 333 MT of CO2-eq emission and total cost saving of USD50 000 annually. This study proves that industrial hazardous waste can be a source of fuel with positive economic and environmental returns. Besides, it was noted from the study that while direct combustion of solid-derived fuels can efficiently produce heat, it can also lead to the generation of greenhouse gases during the production and use phases. In summary, to estimate GHG emissions from IWSF production, a Life Cycle Assessment- Carbon Footprint (LCA-CF) should be considered.

Keywords: Hazardous Waste; Carbon Footprint; Solid Fuel, Cradle-To-Grave; Life Cycle Assessment; Cement Industry

Graphical abstract



1. Introduction

Human activities have increased atmospheric CO_2 concentrations by 48 per cent over the last 171 years, exceeding pre-industrial levels observed in 1850 (Barrie & Braathen, 2016). Carbon dioxide (CO_2) is the most significant contributor to global warming. It mostly comes from the combustion of fossil fuel in power plant, industrial activities, and transportation (Metz, Davidson, Bosch, Dave, & Meyer, 2012; Nutongkaew, Waewsak, Chaichana, & Gagnon, 2014; Samsudin, Rahman, & Wahid, 2016; Wamsler, Brink, & Rivera, 2013). Researchers have observed that CO_2 concentrations in the atmosphere have been increasing significantly over the past century. CO_2 released from coal combustion is responsible for over 0.3°C of the 1°C rise in global average annual surface temperatures above pre-industrial levels, making it one of the most significant contributors to anthropogenic climate change. Furthermore, coal combustion is responsible for 46% of global CO_2 emissions and 72% of overall GHG emissions from the electricity sector (Olivier & Peters, 2018). The greenhouse gas emissions are reported in units of carbon dioxide equivalent (CO_2e). The CO_2e accounts for carbon dioxide and other gases, including methane, nitrous oxide, and others.

In Malaysia, coal is the primary fuel for energy supply due to its affordable price and availability (Samsudin et al., 2016). In 2019, approximately 0.9 exajoules of coal were consumed in Malaysia. It was estimated that the demand for coal would increase to 37.4 million tons in 2030. Currently, Malaysia imported as much as 98 % of that coal burned to generate about 40% of the country's electricity. In 2018, we were the 8th largest importer in the world of coal briquettes and the 12th largest importer of bituminous coal. A high-temperature kiln, often fuelled by coal, heats the raw materials to a partial melt at 1450°C, transforming them chemically and physically into a substance known as clinker. Generally, one ton of cement consumed an average of 3.3 GJ of energy, equivalent to 120 kg of coal (Sarawan & Wongwuttanasatian, 2013). One ton of cement production releases 0.65 – 0.95 tons of CO_2, depending on the efficiency of the processes, fuel types, and types of cement produced.

Due to the rising demand for coal usage and significant contribution to CO_2 emission, it is necessary to find alternatives to coal. In the future energy system, biomass would be an essential source of renewable resources, heat, fuels, and chemicals (Schulzke, 2019). Solid fuel has become one of the alternative renewable energy resources. It can replace conventional fossil fuels, mainly coal in the cement kiln industry and coal-powered plants (Zhengang, Weerasiri, & Dissanayake, 2011). Solid fuel is an innovation of the wastes-to-energy concept. The safe handling and recycling of wastes and the management of greenhouse gas production are essential to address waste management. Solid waste treatment methods play some degree of impact on global warming (Arshadi & Yaghmaei, 2020). Solid fuel is derived from recyclable municipal solid wastes or industrial solid wastes (Kara, 2012; Szűcs & Szentannai, 2021) with an average heating value of 3,000 kcal/kg 6,000 kcal/kg (Chen et al., 2012). The study conducted by Chen and others (2011) shows that when Refused Drive Fuel (RDF) is used as feedstock for producing electricity in Refuse Recycling Centre/Waste to Energy (RRC/WtE) facility, the carbon footprint of electricity is reduced to 0.14 kg/kWh as compared to the national electric power in Malaysia at 0.60 kg/kWh (Chen, Ismail, Adnan, & Ramasamy, 2011).

This paper aimed to propose methodologies and evaluate the carbon footprint of the different stages of industrial waste-based solid fuel (IWSF). While direct combustion of solid-derived fuels can efficiently produce heat, it can also lead to global warming during the production and use phases. Life Cycle Assessment- Carbon Footprint (LCA-CF) should be considered to estimate GHG emissions from IWSF production. LCA is a globally accepted framework for accounting for upstream and downstream inputs and emissions associated with a product or service (Muralikrishna & Manickam, 2017). Carbon footprint (CF) is a relative measurement of CO_2 release on the environment from the production, use, and end-of-life of a product or activity. The use of waste as a replacement for primary materials always be addressed by waste management. Waste reuse should be seen as a method of mitigating emissions. One of the most important factors to consider when investing in waste to energy is the calculation of co-effectiveness. The in-depth assessment of the CF of the pre-collection stage, collection, transport stages, and treatment stage of the RDF developed have been illustrated in this paper. This work limited to the LCA of IWSF production. The results obtained in the study can help policymakers to assess CF produced by IWSF and compared it with using coal in the cement manufacturing plant.

2. Materials and methods

2.1. The Life Cycle Assessment-Carbon Footprint

The Life Cycle Assessment (LCA) methodology was used to calculate the Carbon footprint of IWSF production. Carbon Footprint standard ISO 14067 (The Carbon Footprint of a Product) provides a standardized method for quantifying the total greenhouse gases (GHG) emissions generated during the life cycle assessment of a product (Šerkinić, Majić Renjo, & Ucović, 2020). The life cycle stage includes cradle to grave, cradle to gate, gate to gate, and partial life cycle. The assessment considers all raw materials, transports, manufacturing process, usage, and disposal of the product. The method excludes the quantification of GHG emissions from the transportation of workers to the workplace, human energy inputs to the process, and wastes generated from the administrative activities in the manufacturing plant (Wang, Wang, & Yang, 2018). The GHG considered in the assessment is listed in IPCC, defined as a global warming potential of 100 years. The gases are expressed as CO_2 equivalent (CO_2-eq).

2.2. Functional unit

The functional unit for this study provides a quantified reference for all relevant inputs and outputs in the complete life cycle of IWSF. The available unit is defined as a kilogram of carbon dioxide equivalent per megajoule of energy generated from the complete combustion of IWSF CF is expressed in kg CO_2 eq/MJ.

2.3. System Boundary and Time Frame

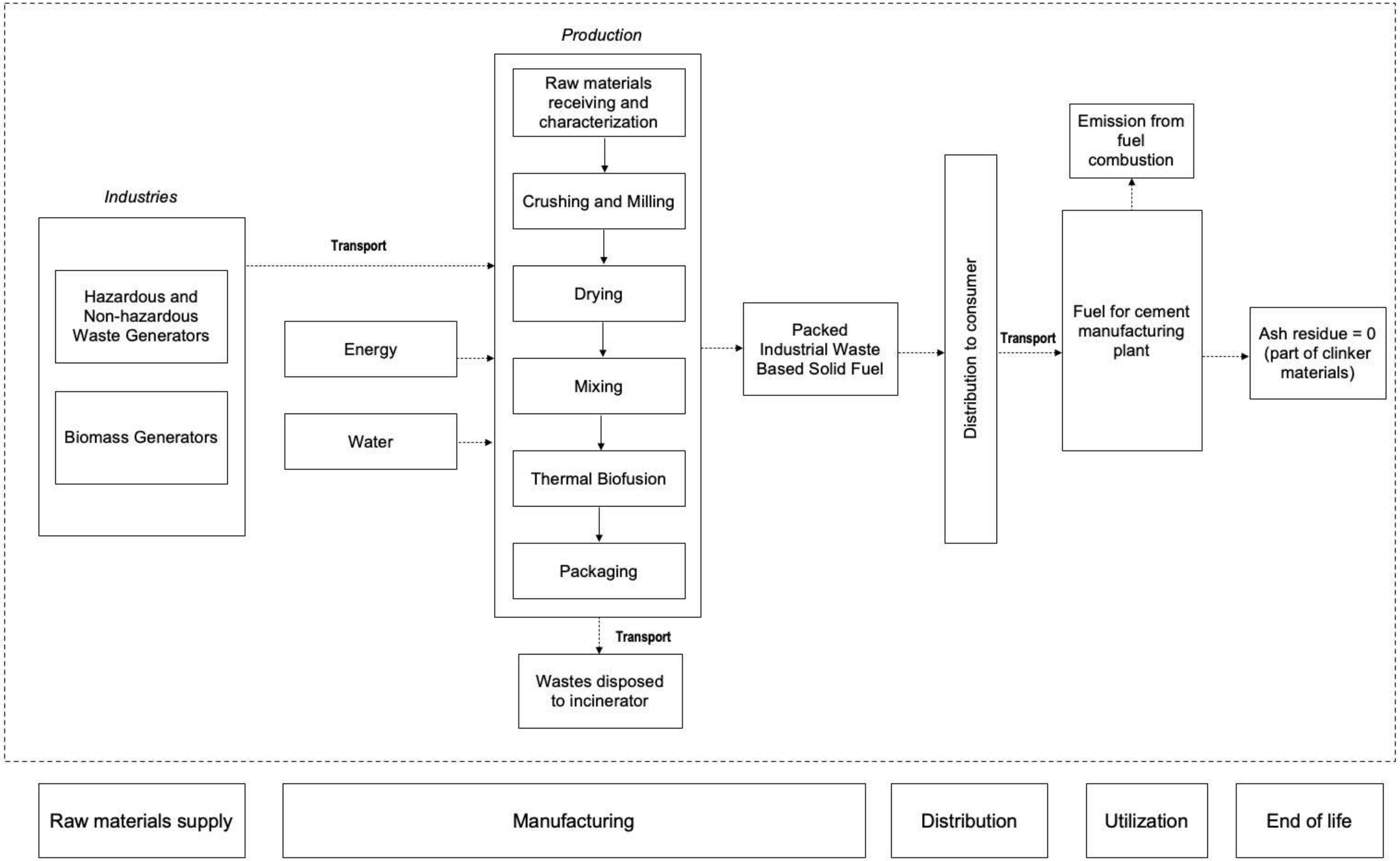
The carbon footprint quantifies greenhouse gas emissions, including CO_2, N_2O and CH_4 emitted from the complete life cycle of IWSF, expressed as carbon dioxide equivalent (CO_2-eq). The cradle-to-grave system boundary for evaluating the carbon footprint of IWSF is illustrated in Figure 1, while the detailed sources of CO_2-eq emissions according to every stage of the life cycle of the IWSF are shown in Table 1. Data sets used for this study are based on complete data for 12 months.

2.4. Raw materials supply

Raw materials used for the production of IWSF are a combination of hazardous wastes, non-hazardous wastes, and biomass from industries in Malaysia. Table 2 shows the details of raw materials used in this study.

Table 1: Sources of CO_2-eq emission according to life cycle stages

Life cycle stages	**Sources of CO_2-eq emission**
Raw materials supply	Vehicle fuel consumed for transportation of raw materials to IWSF manufacturer.
Manufacturing	Water, electricity, and fuel consumed for facilities, and energy is consumed for on-site vehicles.
Distribution to consumer	Vehicle fuel is consumed for the transportation of IWSF to the cement manufacturing plant.
Utilization	Combustion of IWSF for the cement rotary kiln operation.
Disposal of wastes generated from manufacturing plant	Vehicle fuel is consumed for transportation of wastes to disposal facility and emissions released from the incineration of wastes.
End of life	Emissions are released from the incineration of ash residues generated from the utilization of IWSF. However, the IWSF is fully utilized in cement rotary kiln and did not generate any ash residue in this study. Thus, no emissions from this life cycle stage are evaluated in this study.



Production
Raw materials receiving and characterization
Crushing and Milling
Drying
Mixing
Thermal Biofusion
Packaging
Industries
Hazardous and Non-hazardous Waste Generators
Biomass Generators
Transport
Energy
Water
Packed Industrial Waste Based Solid Fuel
Distribution to consumer
Transport
Emission from fuel combustion
Fuel for cement manufacturing plant
Ash residue = 0 (part of clinker materials)
Transport
Wastes disposed to incinerator
Raw materials supply
Manufacturing
Distribution
Utilization
End of life

Figure 1: A schematic overview of the IWSF supply chain and the system boundary

Table 2: Types of raw materials used for IWSF

Raw materials	Type of wastes	Source of industries
Industrial hazardous wastes	Rubber waste, paint, and wastewater sludge	Automotive, chemicals, polymers, optical lens, wastewater treatment plant, rubber gloves, paper mills.
Industrial non-hazardous wastes	Expired food additives and oleochemical wastes	Food manufacturing, oleochemical.
Biomass	Sawdust	Sawmill and timber industry.

2.5. Production of industrial wastes based on solid fuel

Hazardous and non-hazardous industrial wastes with average moisture and calorific value of 35% and 2,500 kcal/kg, respectively, are used as the raw materials for the manufacturing of IWSF, together with 3,000 $kcal.kg^{-1}$ of biomass. The industrial wastes are stored in loose form to increase natural drying, which resulted in an average of 5% moisture content reduction. The industrial wastes are then crushed in a milling machine to a size less than 20 mm and transferred into the natural gas-fired rotary dryer, with an inlet air temperature of 250°C - 280°C for 10 hours. The biomass separately crushed to a size less than 20 mm and fed into the dryer for 5 hours. The drying process for industrial wastes and biomass resulted in an average reduction of 20% moisture content.

Additionally, the dryer has a twin cyclone, a bag filter, and a wet venturi scrubber system for air pollution control. Subsequently, the industrial wastes and biomass are mixed homogenously and fed into the thermal bio fusion machine for the briquette process. The final product, industrial waste-based solid fuel, with an average calorific value of 3,200 kcal.kg-1, is placed in a loose form in a storage area before delivery to the cement plant. The manufacturing process flow chart is given in Figure 2. As for the resources consumed in the manufacturing plant, city water is used for the overall manufacturing activities, primarily for the wet venturi scrubber and other non-process use. Piped-in natural gas is used as the fuel source at the rotary dryer. Grid electricity is purchased for all electrical needs of the facility in the plant. The plant operates four diesel-fuelled and petrol-fuelled forklift trucks for material handling purposes within the plant.

2.6. Case study

Approximate 12,000 MT of produced IWSF is utilized annually as an alternative fuel for coal replacement in a cement manufacturing plant located in Negeri Sembilan, Malaysia. The IWSF is selected as the alternative fuel due to better usability in terms of its availability and supply, calorific value consistency of 3,200 $kcal.kg^{-1}$ compared to the average calorific value of Indonesian bituminous coal of 4,500 $kcal.kg^{-1}$

and its low moisture content of 20%. A study was conducted at the cement manufacturing plant to evaluate the performance of IWSF as a supplementary fuel by assessing the effectiveness of its utilization on the quality of clinker produced to determine the feasibility of substituting Indonesian bituminous coal with IWSF. The study was conducted by evaluating the use of 100% Indonesian bituminous coal at 35 tons.hr^{-1} compared to the use of 45% IWSF and 55% Indonesian bituminous coal at 5 tons/hr (Karpan, Abdul Raman, & Taieb Aroua, 2021). Table 3 shows the results obtained from the study on the effect of the clinker quality. The results show that all clinker quality parameters comply with the Malaysian Cement Standard.

Furthermore, the substitution of 5 ton.hr^{-1} of IWSF for the Indonesian bituminous coal only emitted approximately 301 mg.m^{-3} of NOx, which complies with the Malaysian limits. Besides, heavy metals, including Zinc, Arsenic, Lead, Copper, Antimony and Chromium, also met the Malaysian standard compliance. Additionally, based on carbon monoxide monitoring, it was noted that the use of IWSF at a higher input rate generated less CO emission compared to other alternative fuels.

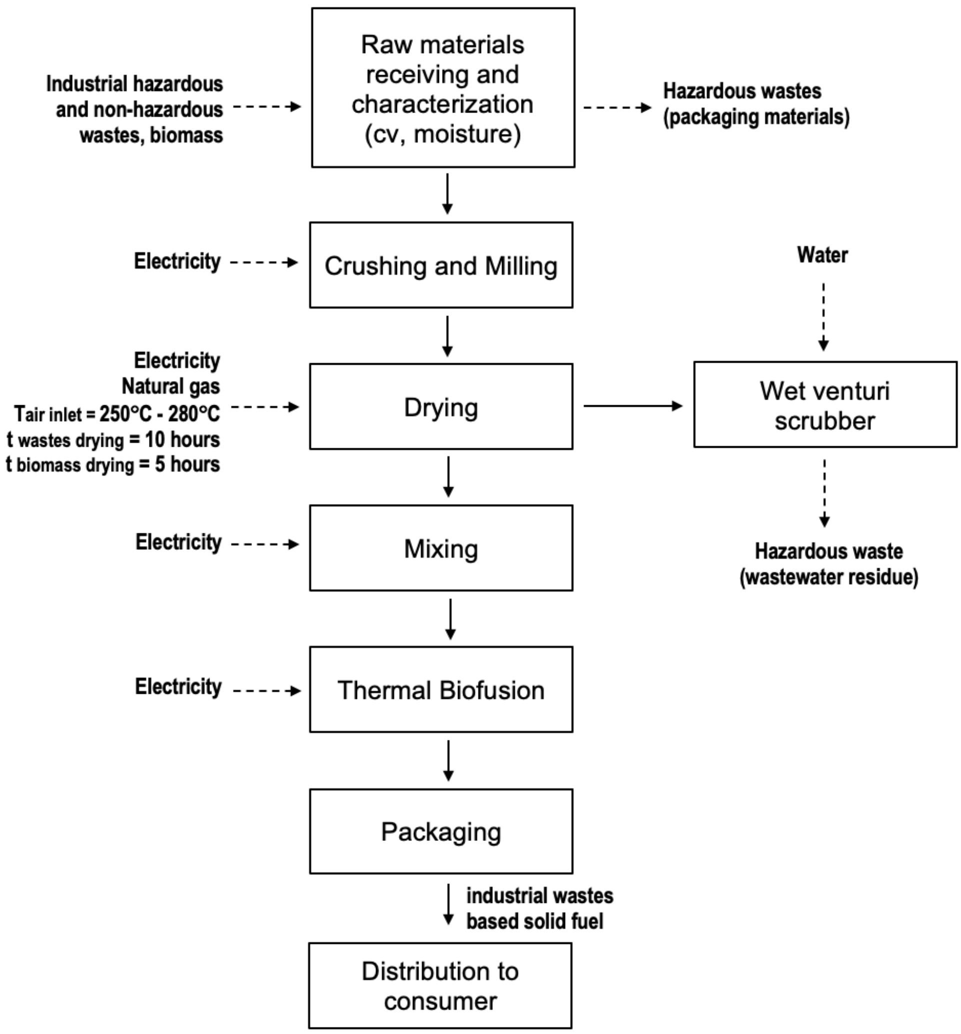


Figure 2: Manufacturing process flow of IWSF

Table 3: Clinker quality information

Parameters	Measurement result		Malaysian Cement Standard limits
	100% coal	IWSF + Coal	
Loss on ignition	0.33	0.25	0.02 – 0.43
Silica	21.21	21.33	19.98 – 22.94
Alumina	4.48	4.76	4.02 – 5.37
Ferric Oxide	3.34	3.50	2.61 – 4.51
Calcium Oxide	67.9	67.76	66.03 – 70.21
Magnesium Oxide	0.96	0.91	0.06 – 2.31
Sulfur Trioxide	1.12	0.89	0.34 – 1.75
Potassium Oxide	0.51	0.54	0.31 – 0.69
Free Lime	1.34	1.57	0.45 – 7.11
Lime saturation factor	101.71	100.21	93.23 – 107.43
Silica modulus	2.71	2.58	2.14 – 3.12

2.7. Quantification of CF

2.7.1. Disposal of wastes

Wastes generated from the manufacturing activities include packaging material from the incoming industrial wastes and residue from the wet venturi scrubber. Licensed contractors collect the wastes classified as hazardous wastes with the frequency of collection of 47 times a year. In this study, the garbage generated is assumed to be incinerated at the disposal facility.

2.7.2. End of life

The IWSF is fully utilized during the cement rotary kiln operation. The ash residues generated during solid fuel combustion are also part of the cement clinker materials. This can be supported by (Lam & McKay, 2010), which has studied the feasibility of replacing clinker raw materials with ash residue for cement clinker manufacturing. Therefore, the end-of-life of IWSF does not generate any ash residue from the utilization stage.

2.7.3. Transportation

Transportation is divided into three stages; 1) transportation of raw materials from wastes and biomass generators to the manufacturing plant using a company-owned diesel-fueled lorry, 2) transportation to the consumer, and 3) transportation of hazardous waste generated from the manufacturing plant to the waste disposal facility using the third party owned diesel-fueled lorry. Table 4 shows the details of transportation included in this study, according to respective stages.

Table 4: Details of transportation

Life cycle stage	Type of vehicle	Capacity (MT)
TP1: Raw materials to manufacturing plant	40' and 20' lorry	8.5 and 16
TP2: IWSF manufacturer to consumer	40' lorry	30
TP3: Disposal of wastes generated from manufacturing plant to the disposal facility	5' lorry	1

2.8. Summary of materials and energy flow

Table 5 shows the input-output of materials and energy flows and other related information involved in this study. Hence, the calculation for quantifying CO_2-eq emission generated is using the data included in Table 5.

Table 5: Input-output details

Life cycle stage	Sources of CO_2-eq emission	Quantity per year
Raw material supply	Wastes	12,338.1 MT
	Biomass	2,490.3 MT
Transport, TP1 $_{\text{RMG to SFM}}$	Total distance	419,805.8 km
	Fuel consumption	138,329.3 L
Transport, TP2 $_{\text{SFM to SFC}}$	Total distance	82,400.0 km
Transport, TP3 $_{\text{SFM to WDF}}$	Total distance	28,668.0 km
Manufacturing of IWSF	Water consumption	1,506.0 m^3
	Diesel consumption	25,231.7 L
	Petrol consumption	2,559.4 L
	Natural gas consumption	7,615.0 mmBtu
	Electricity consumption	392,915.0 kWh
Utilization of IWSF	Solid fuel output	12,330.0 MT
Waste disposal	Scheduled waste	257.3 MT
End of life	Ash residue	0

3. Results and Discussion

3.1. Carbon footprint quantification

a. CO_2-eq emission factors

The emission factors are represented as carbon dioxide equivalent (CO_2-eq) by multiplying CO_2, N_2O, and CH_4 emissions with their respective Global Warming Potential (GWP) coefficient based on the Intergovernmental Panel on Climate Change (IPCC) 100-years GWP coefficients. GWP coefficient from

IPCC Fifth Assessment Report, 2014, which is 1, 285, and 28 for CO_2, N_2O, and CH_4, respectively, were used in this study (Pachauri et al., 2014). Table 6 shows the emission factors used in this study.

Table 6: CO_2-eq emission factors

Sources of CO_2-eq emission	CO_2-eq Emission Factor
Water	0.344 kg CO_2-eq. m^{-3}
Purchased electricity	0.585 MT CO_2-eq. MWh^{-1}
Natural Gas (stationary)	0.056 MT CO_2-eq. $mmBtu^{-1}$
Diesel (mobile)	0.0027 MT CO_2-eq. L^{-1}
Diesel (mobile)	0.880 kg CO_2-eq. km^{-1}
Petrol (mobile)	0.0023 MT CO_2-eq. L^{-1}
Waste incinerated	1.679 MT CO_2-eq. $MT_{\text{waste incinerated}}^{-1}$

An inventory of CO_2-eq emission by the source was calculated by applying the CO_2-eq emission factors to relevant activity data to quantify the carbon footprint of IWSF. The calculation adopted methodological approach by 1996 Intergovernmental Panel on Climate Change Guidelines, where the basic equation is:

$$Emission = AD \times EF \tag{1}$$

where:

$AD = Activiti\ Data$

$EF = Emission\ Factor$

b. CO_2-eq emission from raw materials supply

The raw materials used for the manufacturing of IWSF are industrial hazardous and non-hazardous wastes obtained from other industrial plants. Hence, the CO_2-eq emission generated due to raw materials extraction is not considered in this study.

c. CO_2-eq emission from transportation

The CO2-eq emission from transportation was calculated using (Eq. 2)

$$E_T = E_t(RMG\ to\ SFM) + E_t(SFM\ to\ SFC) + E_t(SFM\ to\ WDF) \quad (2)$$

where components of the formula in detail:

$E_t(RMG\ to\ SFM) = total\ distance\ (km.year^{-1}) \times ef(L.km^{-1}) \times EF_{\ diesel}\ (MT\ CO_{2-eq}\ .\ L^{-1})$

$E_t(SFM\ to\ SFC) = total\ distance\ (km.year^{-1}) \times EF_{\ diesel}\ (kg\ CO_{2-eq}\ .\ km^{-1})\ /\ 1000$

$E_t(SFM\ to\ WDF) = total\ distance\ (km.year^{-1}) \times EF_{\ diesel}\ (kg\ CO_{2-eq}\ .\ km^{-1})/\ 1000$

$E_T = total\ emission\ from\ transport\ (MT\ CO_{2-eq}\ .\ year^{-1})$

CO_2-eq emission from company-owned transport (E_t), data were collected on-site, where the respective distance was measured, and fuel efficiency (ef) was monitored to measure the total fuel consumed. Thus, the CO_2-eq emission factor used is in the unit of (MT CO_2-eq. $L^{-1}{}_{diesel}$). However, for non-owned transport to dispose of wastes generated from the IWSF manufacturing plant and deliver IWSF to the consumer, data were collected by measuring the total distance and the total number of trips. Thus, the CO_2-eq emission factor used is in the unit of (kg CO_2-eq. $km^{-1}{}_{travelled}$). CO_2-eq emission from the manufacture of vehicles is not considered in this study.

d. CO_2-eq emission from the manufacturing of IWSF

CO_2-eq emission from the manufacturing of IWSF (E_P), data were collected on-site, where the respective quantities were measured and extracted from respective operating documents. CO_2-eq emission from the manufacture of machinery and equipment is not considered in this study, and CO_2-eq emission from the treatment of domestic wastewater used by workers in the production plant and CO_2-eq emission from the treatment of domestic wastes generated from administrative activities. The calculation is based on the following formula (Eq. 3).

$$E_M = E_{electricity\ consumption} + E_{water\ consumption} + E_{diesel\ consumption} + E_{petrol\ consumption} + E_{NG\ consumption} \quad (3)$$

where components of the formula in detail:

$E_{electricity\ consumption} = electricity\ (kWh\ .year^{-1}) \times EF_{electricity}\ (MT\ CO_{2-eq}\ .\ MWh^{-1})/1000$

$E_{water\ consumption} = water\ (m^3.year^{-1}) \times EF_{water}\ (kg\ CO_{2-eq}\ .\ m^{-3})$

$$E_{diesel\ consumption} = diesel\ (L\ .year^{-1}) \times EF_{diesel}\ (MT\ CO_{2-eq}\ .\ L^{-1})$$

$$E_{petrol\ consumption} = petrol\ (L\ .year^{-1}) \times EF_{petrol}\ (MT\ CO_{2-eq}\ .\ L^{-1})$$

$$E_{NG\ consumption} = NG\ (mmBtu\ .year^{-1}) \times EF_{NG}\ (MT\ CO_{2-eq}\ .\ mmBtu^{-1})$$

$$E_M = total\ emission\ from\ manufacturing\ (MT\ CO_{2-eq}\ .\ year^{-1})$$

e. CO_2-eq emission from waste disposal

f. The is CO_2-eq emission from waste disposal is calculated using Eqn. 4:

$$E_{WD} = E_W \tag{4}$$

where the component of the formula is as follows:

$$E_W = wastes\ from\ manufacturing\ plant\ (MT\ .\ year^{-1}) \times EF_{\ W\ incinerated}\ (MT\ CO_{2-eq}\ .\ MT^{-1})$$

$$E_{WD} = total\ emission\ from\ waste\ disposal\ (MT\ CO_{2-eq}\ .\ year^{-1})$$

CO_2-eq emission from waste disposal (E_{WD}) collected on-site data, where the respective quantities were measured.

g. CO_2-eq emission from the use of IWSF

The CO_2-eq emission from a cement manufacturing plant is originated from the decarbonization of the raw materials ($CaCO_3 \rightarrow CaO + CO_2$) and combustion of carbon ($C + O_2 \rightarrow CO_2$) in the fuels used for providing energy for the overall endothermic reactions in the kiln system (Lin, Kiga, Wang, & Nakayama, 2011; Wojtacha-Rychter, Kucharski, & Smolinski, 2021). Hence, the emissions generated from the combustion of IWSF in a cement manufacturing plant were predicted via the stoichiometric method. Elemental CHNOS analysis was conducted to determine carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and sulfur (S) content. The results obtained from the analysis are then used to calculate the products of combustion. Table 7 shows the results of elemental CHNOS Analysis.

Table 7: CHNOS results

Test Parameter	Weight (%)
Carbon, C	59

Hydrogen, H	6
Nitrogen, N	3
Sulphur, S	0.61
Oxygen, O	12

The equation for complete combustion of CHNOS and ratio of moles between reactants and products are as follows:

C	:	$C + O_2 \rightarrow CO_2$	1 mol C $\rightarrow$ 1 mol CO_2
H	:	$H_2 + 0.5O_2 \rightarrow H_2O$	1 mol H_2 $\rightarrow$ 1 mol H_2O
N	:	$N_2 + 2O_2 \rightarrow 2NO_2$	1 mol N_2 $\rightarrow$ 2 mol NO_2
S	:	$S + O_2 \rightarrow SO_2$	1 mol S $\rightarrow$ 1 mol SO_2

The calculation of gas emissions from complete combustion is as follows:

Number of mol of the element before combustion

$$N_i = (W_i)/MW_i \tag{5}$$

where:

$N_i = \ no.of\ mol\ of\ element\ i\ (kmol)$

$W_i = \ weight\ fraction\ of\ element\ i\ (obtained\ from\ elemental\ CHNOS\ analysis\ results)$

$MW_i = \ molecular\ weight\ of\ element\ i\ (kg.kmol^{-1})$

Weight of the product (emissions) from combustion

$$E_j = y_j\ (N_j \times MW_j \times W) \tag{6}$$

where:

$E_j = \ Quantity\ of\ emission\ j\ (kg)$

$y_j = \ mol\ ratio\ number\ of\ gas\ j$

$N_j = \ no.\ of\ mol\ of\ gas\ j$

$W = \ total\ weight\ of\ IWBSF$

$MW_j = \ molecular\ weight\ of\ gas\ j\ (kg.kmol^{-1})$

Emissions generated from the complete combustion of IWSF in cement manufacturing plants are CO_2, SO_2, and NO_2. However, SO_2 and NO_2 are not included as GHG in IPCC, and hence for the IWSF utilization stage, this study only considered emission of CO_2, E_{use}. In addition, this study also included N_2O emission released from the combustion of IWSF. CH_4 was omitted as the emissions are usually minimal and insignificant (Guendehou, Koch, Hockstad, Pipatti, & Yamada, 2006).

h. CO_2-eq emission from the end life of IWSF

The ash residues generated from the combustion of IWSF are used as the raw materials for cement clinker manufacturing (Lam & McKay, 2010). Hence, E_{EL} is assumed zero.

i. CO_2-eq emission from the full life cycle of IWSF

Therefore, the total CO_2-eq emission of the IWSF life cycle is calculated based on the following formula (Eqn. 7)

$$E_{IWBSF} = E_M + E_T + E_{WD} + E_{utilization} + E_{EL} \tag{7}$$

where components of the formula in detail:

E_{IWBSF}	$total\ emissions\ of\ IWBSF\ life\ cycle$
E_M	$total\ emissions\ from\ manufacturing$
E_T	$total\ emissions\ from\ transport$
E_{WD}	$total\ emissions\ from\ waste\ disposal$
$E_{utilization}$	$total\ emissions\ from\ utilization$
E_{EL}	$total\ emissions\ from\ end\ of\ life$

The result shows that the total CO_2-eq emission generated from the cradle-to-grave life cycle of IWSF is approximately 28,637 MT. Year $^{-1}$, which is equal to 0.17 kg CO_2e. $MJ^{-1}_{energy\ generated}$. The result is summarized in Table 8. Figure 3 illustrates the details of materials, energy, and CO_2-eq emission flows obtained in this study.

Table 8: Summary of the carbon footprint of IWSF

CO_2-eq emission source (life cycle stage)	Emission symbol	CO_2-eq (MT. year $^{-1}$)
Transport	E_T	473.9
Manufacturing	E_M	730.9
Waste disposal	E_{WD}	431.4
Utilization	$E_{utilization}$	27,000.7
End of life	E_{EL}	0
Total	E_{IWBSF}	28,636.9

The sources of CO_2-eq emission based on the life cycle stages and their emission percentages are illustrated in Figure 4. It shows that the utilization of IWSF at a cement manufacturing plant is the key contributor to IWSF's carbon footprint, contributing to 94.3% of the total percentage, with a quantitative value of 28,637 MT CO_2-eq per year. Therefore, the utilization stage can be considered as the environmental hotspot for this study. Furthermore, the second-highest contributor is the IWSF manufacturing stage, with a percentage of 2.6. This stage can also be focused on improvement potentials

3.2. Comparison of CO_2-eq emission of IWSF with the other fuel

GHG emissions might be discharged instantly or over overtime of a materials management strategy. There is a lot of uncertainty regarding determining the timing of GHG emissions from waste management. The production of GHG analysis is based on an estimate of industry average energy use. The CO_2–eq emission of IWSF developed in this study has been compared with the other published work. As shown in Table 9, the CO_2–eq emission of IWSF is significantly lower than that of other RDF derived from municipal solid waste (MSW). It has been observed that solid fuels derived from hazardous waste reduce environmental burdens, particularly GHG emissions.

Table 9: Comparison of GHG of IWSF with other fuel

Type of Fuel	kg CO_2-eq	Reference

IWSF	0.170	This study
RDF -MSW	1.697	(Nutongkaew et al., 2014)
RDF-Palm Kernel Shell	1.423	
Battelle (RDF)	1.250	(Nuss, Gardner, & Bringezu, 2013)
MTCI (RDF)	1.019	

3.3. CO_2-eq emission reduction initiatives

According to the carbon footprint analysis of IWSF, CO_2-eq emissions are primarily caused by the disposal of wastes produced during the production process at the IWSF plant. Figure 5 shows that IWSF manufacturing contributed 37 per cent of total CO_2-eq emissions, followed by CO_2-eq emissions from natural gas and electricity use in the manufacturing plant, which contributed 36 and 20 per cent, respectively. In this study, two improvement measures are identified and implemented by the IWSF's manufacturer based on the CF quantification to reduce CO_2-eq emissions produced by electricity during manufacturing activities. The initiatives are evaluated in terms of environmental and economic returns. The economic evaluation focused on monthly savings, while the environmental assessment focused on CO_2-eq emission reduction.

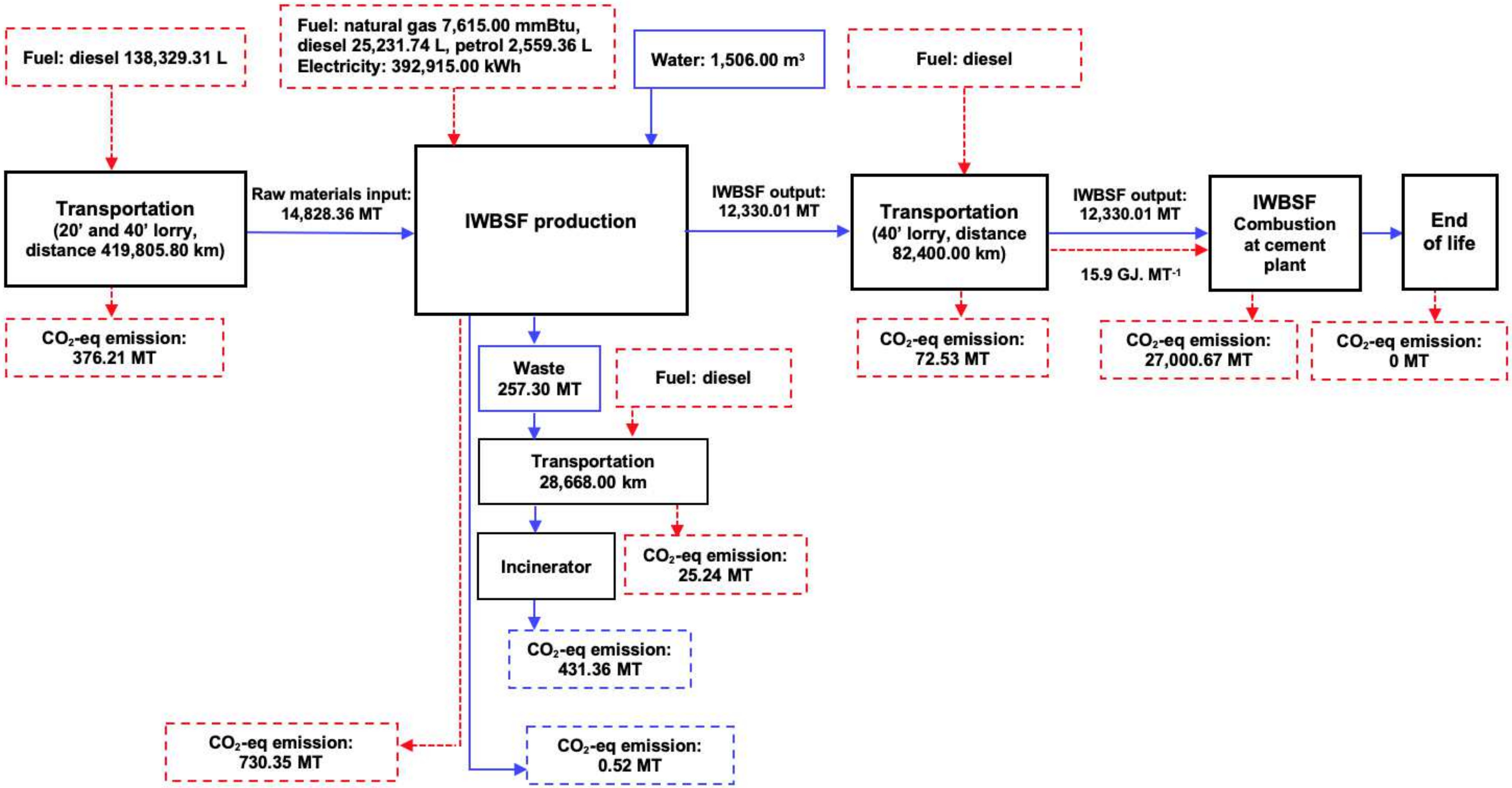

Fuel: diesel 138,329.31 L
Fuel: natural gas 7,615.00 mmBtu, diesel 25,231.74 L, petrol 2,559.36 L Electricity: 392,915.00 kWh
Water: 1,506.00 m³
Fuel: diesel
Transportation (20' and 40' lorry, distance 419,805.80 km)
Raw materials input: 14,828.36 MT
IWBSF production
IWBSF output: 12,330.01 MT
Transportation (40' lorry, distance 82,400.00 km)
IWBSF output: 12,330.01 MT
15.9 GJ. MT-1
IWBSF Combustion at cement plant
End of life
CO2-eq emission: 376.21 MT
CO2-eq emission: 72.53 MT
CO2-eq emission: 27,000.67 MT
CO2-eq emission: 0 MT
Waste 257.30 MT
Fuel: diesel
Transportation 28,668.00 km
Incinerator
CO2-eq emission: 25.24 MT
CO2-eq emission: 431.36 MT
CO2-eq emission: 730.35 MT
CO2-eq emission: 0.52 MT

Figure 3: Flow analysis of materials, energy, and CO_2-eq emission

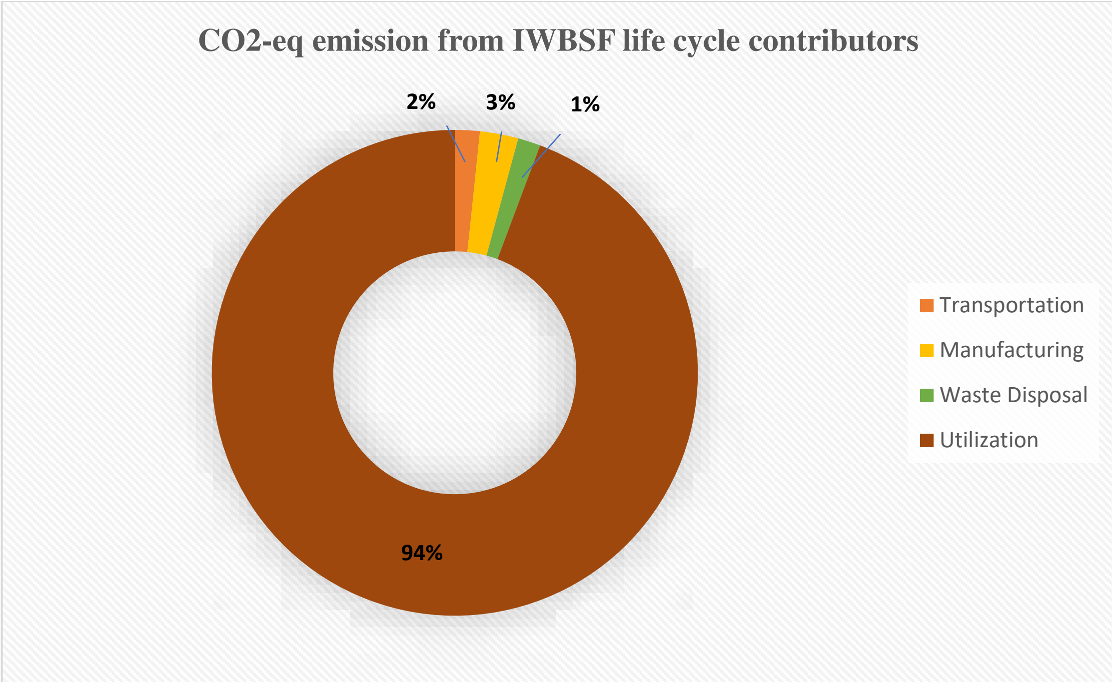


Figure 4: Breakdown of CO_2-eq emission contributors according to respective life cycle stages

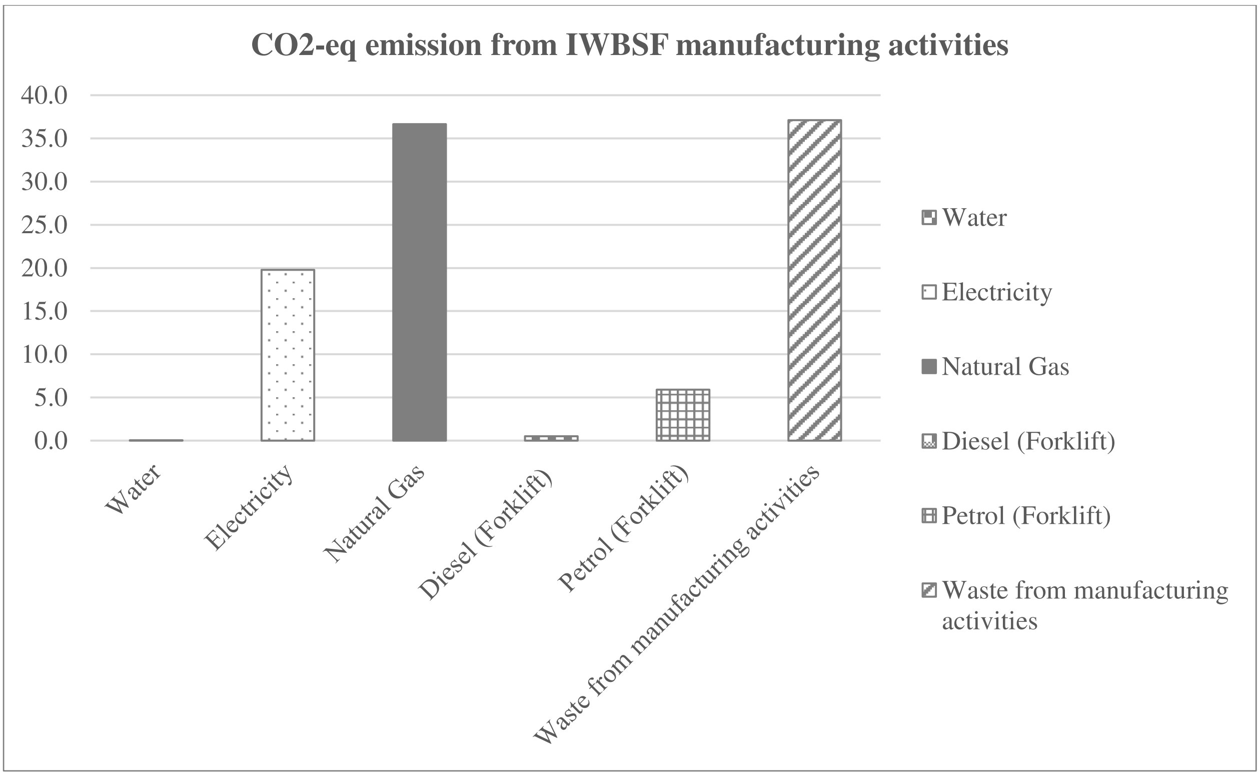


Figure 5: Breakdown of CO_2-eq emission contributors in manufacturing activities

As shown in Table 9, it was identified that the IWSF manufacturing plant consumed high electricity due to the use of a rotary dryer and thermal bio fusion machine. The installations of solar panel units can generate 700 - 900 kWh of power per day. Thus, 66.5% of electricity savings are achieved, which translated into 49,558 USD/year. Energy-saving light-emitting diode (LED) bulbs are installed to replace the existing conventional fluorescent bulbs. In this study, LED bulbs can reduce 42% of electricity usage in the lighting system, translated into 126 USD/year. Subsequently, solar panel units and LED light bulbs are equivalent to an annual CO_2-eq emission reduction of 332 tons and 0.84 tons, respectively. Table 10 summarizes the improvement initiatives with their corresponding outcomes on CO_2-eq emission reduction and cost savings. In addition to the improvement initiatives implemented, the manufacturing plant is also practising other improvement initiatives that are not requiring any investment, mainly in good housekeeping practices.

Table 9: Sources of electricity consumption in IWSF manufacturing plant

Source of electricity consumption	**Consumption (kWh per month)**
2 units of 90 kW thermal bio fusion machine	4320.0
40 kW of mixer	1920.0
40 kW of crusher	2880.0
180 kW of rotary dryer	21600.0
Others (air conditioning, lighting, etc.)	2022.9

Table 10: Summary of economic and environmental evaluation of electricity improvement initiatives

No.	**Improvement initiatives**	**Estimated annual outcome**	
		Cost-saving (USD)	**CO_2-eq emission reduction (MT)**
1	Installation of solar panel units	49,558	332
2	Installation of LED energy-saving bulbs for lighting system (LED T5, 28W x 4 units and LED T8, 20W x 6 units)	126	0.84

4. Conclusion

This research quantifies the carbon footprint of solid fuel derived from industrial wastes over its entire life cycle. Based on an analysis of complete one-year data, the total carbon footprint of IWSF is approximately 28,637 MT of CO2-eq for 12,330 MT of fuel used. The use of IWSF in cement manufacturing plants is the most prevalent life cycle point, accounting for 94.3 per cent of the total percentage. Based on the selected functional unit, the carbon footprint of IWSF can be presented as 0.17 kg CO_2-eq. MJ^{-1} energy generated. In addition to quantifying its carbon footprint, the CO2-equivalent pollution reduction measures have been proposed, emphasizing lowering electricity consumption during the production processes of IWSF. The results show that by implementing CO2-eq emission reduction measures, approximately 333 MT of CO2-eq emissions can be reduced, with a gross cost savings of USD50,000 per year. The use of waste recycling is becoming increasingly necessary to minimize resource consumption. Thus, it is needed to evaluate recycling's environmental benefits and reuse the waste in future work.

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Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence this work.

Statement of Novelty

The carbon footprint (CF) of Refused Derived Fuel (RDF) produced from hazardous waste is evaluated in comparison to commercial coal in this study. There has been no investigation on the quantification of greenhouse gases in RDF produced from waste, particularly hazardous waste, to date.

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