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

Balasubramaniam Karpan  
University of Malaya: Universiti Malaya

Abdul Aziz Abdul Raman  
(azizraman@um.edu.my)  
University of Malaya: Universiti Malaya

Razuana Rahim  
University of Malaya: Universiti Malaya

Kheireddine Taieb Aroua  
Universiti Malaya

Archina Buthiyappan  
University of Malaya: Universiti Malaya

Research Article

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

Posted Date: July 7th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-553149/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Carbon Footprint Evaluation of Hazardous Waste Based Solid Fuel: Application in a Cement Kiln

Balasubramaniam Karpan¹, Abdul Aziz Abdul Raman¹*, Razuana Rahim¹, Mohamed Kheireddine Taieb Aroua² and Archina Buthiyappan¹

¹Department of Chemical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.
²Centre for Carbon Dioxide Capture and Utilization, School of Science and Technology, Sunway University, 47500 Petaling Jaya, Selangor, Malaysia

*Corresponding author. Tel.: +60 3 7967 7700; Fax: +60 3 7967 7733
E-mail address: azizraman@um.edu.my

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 (CO₂-eq). The CO₂-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 CO₂-eq per year IWSF manufacturing stage with 2.6 %. Subsequently, CO₂-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

Raw material

Delivery of Raw material

376.2 MT. year\(^{-1}\)

CO\(_2\)-eq

Manufacturing of IWSF

730.9 MT. year\(^{-1}\)

CO\(_2\)-eq

Disposal of Waste from manufacturing process

431.4 MT. year\(^{-1}\)

CO\(_2\)-eq

Transportation IWSF to cement plant

97.7 MT. year\(^{-1}\)

CO\(_2\)-eq

Utilization of IWSF in Cement Plant

27,000.7 MT. year\(^{-1}\)

CO\(_2\)-eq

End of Life of IWSF

Industrial Waste Based Solid Fuel IWSF
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$_{2}$e). The CO$_{2}$e 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; Szücs & 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$_2$O 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          | Vehicle fuel is consumed for transportation of wastes to disposal facility and emissions released from the incineration of wastes.                                      |
| manufacturing plant                        |                                                                                                                                                                  |
| 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. |

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.
Figure 1: A schematic overview of the IWSF supply chain and the system boundary
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\(^\circ\)C - 280\(^\circ\)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\(^{-1}\)

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.                                                         |
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.

| 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 CO₂-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 RMG to SFM | Total distance            | 419,805.8 km     |
|                    | Fuel consumption              | 138,329.3 L       |
| Transport, TP2 SFM to SFC | Total distance            | 82,400.0 km      |
| Transport, TP3 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$_2$O, 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$_2$O, 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 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:

\[ Emission = AD \times EF \] (1)

where:

\[ AD = \text{Activiti Data} \]

\[ EF = \text{Emission Factor} \]

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 CO$_2$-eq emission from transportation was calculated using (Eq. 2)
\[ E_T = E_t(RMG \text{ to } SFM) + E_t(SFM \text{ to } SFC) + E_t(SFM \text{ to } WDF) \] (2)

where components of the formula in detail:

\[ E_t(RMG \text{ to } SFM) = \text{total distance (km.year}^{-1}\text{)} \times ef(L.km}^{-1}\text{)} \times EF_{\text{diesel}}(MT \text{ CO}_2-\text{eq} \cdot L^{-1}) \]

\[ E_t(SFM \text{ to } SFC) = \text{total distance (km.year}^{-1}\text{)} \times EF_{\text{diesel}}(kg \text{ CO}_2-\text{eq} \cdot km}^{-1}\text{)} / 1000 \]

\[ E_t(SFM \text{ to } WDF) = \text{total distance (km.year}^{-1}\text{)} \times EF_{\text{diesel}}(kg \text{ CO}_2-\text{eq} \cdot km}^{-1}\text{)} / 1000 \]

\[ E_T = \text{total emission from transport (MT CO}_2-\text{eq} \cdot \text{year}^{-1}) \]

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 \cdot 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 \cdot km\(_{\text{travelled}}\)). 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).

\[ E_M = E_{\text{electricity consumption}} + E_{\text{water consumption}} + E_{\text{diesel consumption}} + E_{\text{petrol consumption}} + E_{\text{NG consumption}} \] (3)

where components of the formula in detail:

\[ E_{\text{electricity consumption}} = \text{electricity (kWh.year}^{-1}\text{)} \times EF_{\text{electricity}}(MT \text{ CO}_2-\text{eq} \cdot MWh}^{-1})/1000 \]

\[ E_{\text{water consumption}} = \text{water (m}^3\text{.year}^{-1}\text{)} \times EF_{\text{water}}(kg \text{ CO}_2-\text{eq} \cdot m}^{-3} \)
\[ E_{\text{diesel consumption}} = \text{diesel (L.year}^{-1}) \times EF_{\text{diesel}} (MT \ CO_2-\text{eq} . L^{-1}) \]
\[ E_{\text{petrol consumption}} = \text{petrol (L.year}^{-1}) \times EF_{\text{petrol}} (MT \ CO_2-\text{eq} . L^{-1}) \]
\[ E_{\text{NG consumption}} = \text{NG (mmBTu.year}^{-1}) \times EF_{\text{NG}} (MT \ CO_2-\text{eq} . \ mmBTu^{-1}) \]
\[ E_M = \text{total emission from manufacturing (MT CO}_2-\text{eq} . \ year^{-1}) \]

e. **CO}_2-\text{eq emission from waste disposal**

f. The is CO}_2-\text{eq emission from waste disposal is calculated using Eqn. 4:

\[ E_{WD} = E_W \] (4)

where the component of the formula is as follows:
\[ E_W = \text{wastes from manufacturing plant (MT} . \ year^{-1}) \times EF_{\text{incinerated}} (MT \ CO_2-\text{eq} . \ MT^{-1}) \]
\[ E_{WD} = \text{total emission from waste disposal (MT CO}_2-\text{eq} . \ year^{-1}) \]

CO}_2-\text{eq emission from waste disposal (E}_{WD} \text{) collected on-site data, where the respective quantities were measured.**

\[ CO}_2-\text{eq emission from the use of IWSF**

The CO}_2-\text{eq emission from a cement manufacturing plant is originated from the decarbonization of the raw materials (CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2} \) and combustion of carbon (C + O}_2 \rightarrow \text{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.

| Test Parameter | Weight (%) |
|----------------|------------|
| Carbon, C      | 59         |

Table 7: CHNOS results
| Element | Value |
|---------|-------|
| 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:

\[
\begin{align*}
C & : \ C + O_2 \rightarrow CO_2 & & \text{1 mol C} \rightarrow \text{1 mol CO}_2 \\
H & : \ H_2 + 0.5O_2 \rightarrow H_2O & & \text{1 mol H}_2 \rightarrow \text{1 mol H}_2O \\
N & : \ N_2 + 2O_2 \rightarrow 2NO_2 & & \text{1 mol N}_2 \rightarrow \text{2 mol NO}_2 \\
S & : \ S + O_2 \rightarrow SO_2 & & \text{1 mol S} \rightarrow \text{1 mol SO}_2
\end{align*}
\]

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

Number of mol of the element before combustion

\[
N_i = \frac{W_i}{MW_i} \tag{5}
\]

where:

\[
N_i = \text{no. of mol of element } i \text{ (kmol)}
\]

\[
W_i = \text{weight fraction of element } i \text{ (obtained from elemental CHNOS analysis results)}
\]

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

Weight of the product (emissions) from combustion

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

where:

\[
E_j = \text{Quantity of emission } j \text{ (kg)}
\]

\[
y_j = \text{mol ratio number of gas } j
\]
\[ N_j = \text{no. of mol of gas } j \]
\[ W = \text{total weight of IWBSF} \]
\[ MW_j = \text{molecular weight of gas } j \text{ (kg.kmol}^{-1}\text{)} \]

Emissions generated from the complete combustion of IWBSF 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\(_2\)O 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\(_2\)e. 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

| CO2-eq emission source (life cycle stage) | Emission symbol | CO2-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                                    | $E_{IWSF}$      | 28,636.9            |

The sources of CO₂-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 CO₂-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 CO₂-eq emission of IWSF with 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 CO₂–eq emission of IWSF developed in this study has been compared with the other published work. As shown in Table 9, the CO₂–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 CO₂-eq | Reference |
|--------------|-----------|-----------|

20
3.3. \textit{CO}_2\text{-eq emission reduction initiatives}

According to the carbon footprint analysis of IWSF, \textit{CO}_2\text{-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 \textit{CO}_2\text{-eq} emissions, followed by \textit{CO}_2\text{-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 \textit{CO}_2\text{-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 \textit{CO}_2\text{-eq} emission reduction.
Figure 3: Flow analysis of materials, energy, and CO₂-equivalent emission
Figure 4: Breakdown of CO₂-eq emission contributors according to respective life cycle stages
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 CO₂-eq emission reduction of 332 tons and 0.84 tons, respectively. Table 10 summarizes the improvement initiatives with their corresponding outcomes on CO₂-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)        |
|     |                                                                                        | CO₂-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.

Acknowledgement

The authors would like to acknowledge SAGE PROMASTER Sdn. Bhd. and MyBrain15 from Ministry of Higher Education Malaysia for providing financial assistance for this research work.

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.

References

Arshadi, M., & Yaghmaei, S. (2020). Advances in bioleaching of copper and nickel from electronic waste using Acidithiobacillus ferrooxidans: evaluating daily pH adjustment. *Chemical Papers, 74*(7), 2211-2227. doi:10.1007/s11696-020-01055-y

Barrie, L., & Braathen, G. (2016). The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2015. *WMO Greenhouse Gas Bulletin, 15*, 1-8.

Chen, S. S., Ismail, I., Adnan, A. N., & Ramasamy, P. (2011). Refuse Derived Fuel - Case Study of Waste as Renewable Resource. *International Journal for Sustainable Innovations, 1*(1).

Guendehou, G. S. H., Koch, M., Hockstad, L., Pipatti, R., & Yamada, M. (2006). *Guidelines for National Greenhouse Gas Inventories*. Retrieved from

Kara, M. (2012). Environmental and economic advantages associated with the use of RDF in cement kilns. *Resources, Conservation and Recycling 68*, 21–28.

Karpan, B., Abdul Raman, A. A., & Taieb Aroua, M. K. (2021). Waste-to-energy: Coal-like refuse derived fuel from hazardous waste and biomass mixture. *Process Safety and Environmental Protection, 149*, 655-664. doi:https://doi.org/10.1016/j.psep.2021.03.009

Lam, H. K., & McKay, G. (2010). Utilization of Incineration Waste Ash Residues as Portland Cement Clinker. *Chemical Engineering Transactions, 21*, 757–762.
Lin, S., Kiga, T., Wang, Y., & Nakayama, K. (2011). Energy analysis of CaCO3 calcination with CO2 capture. Energy Procedia, 4, 356-361. doi:https://doi.org/10.1016/j.egypro.2011.01.062

Metz, B., Davidson, O., Bosch, P., Dave, R., & Meyer, L. (2012). Contribution of Working Group III to the Fourth Assessment Report of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change 2007. Retrieved from Cambridge University Press, Cambridge, United Kingdom and New York, USA:

Muralikrishna, I. V., & Manickam, V. (2017). Chapter Five - Life Cycle Assessment. In I. V. Muralikrishna & V. Manickam (Eds.), Environmental Management (pp. 57-75): Butterworth-Heinemann.

Nuss, P., Gardner, K. H., & Bringezu, S. (2013). Environmental Implications and Costs of Municipal Solid WasteDerived Ethylene Journal of Industrial Ecology, 17(6), 912–925

Nutongkaew, P., Waewsak, J., Chaichana, T., & Gagnon, Y. (2014). Greenhouse Gases Emission of Refuse Derived Fuel-5 Production from Municipal Waste and Palm Kernel. Energy Procedia, 52 362-370.

Olivier, J., & Peters, J. (2018). Trends in global CO2 and total greenhouse gas emissions. Retrieved from The Hague, Netherlands:

Pachauri, R. K., Meyer, L., Hallegatte France, S., Bank, W., Hegerl, G., Brinkman, S., . . . Boxmeer, F. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. . Retrieved from Kristin Seyboth (USA):

Rahim, R., & Abdul Raman, A. A. (2017). Carbon dioxide emission reduction through cleaner production strategies in a recycled plastic resins producing plant. Journal of Cleaner Production, 141, 1067–1073.

Samsudin, M., Rahman, M., & Wahid, M. (2016). Power Generation Sources in Malaysia: Status and Prospects for Sustainable Development, . Journal of Advanced Review on Scientific Research, 25(1), 11-28.

Sarawan, S., & Wongwuttanasatian, T. (2013). A feasibility study of using carbon black as a substitute to coal in cement industry. Energy for Sustainable Development, 17(3), 257-260.

Schulzke, T. (2019). Biomass gasification: conversion of forest residues into heat, electricity and base chemicals. Chemical Papers, 73(8), 1833-1852. doi:10.1007/s11696-019-00801-1

Šerkinić, V., Majić Renjo, M., & Ucović, V. (2020). CO2 footprint for distribution oil immersed transformers according to ISO 14067:2018. Journal of Energy, 69(3), 3-9.

Szűcs, T., & Szentannai, P. (2021). Developing an all-round combustion kinetics model for nonspherical waste-derived solid fuels. Chemical Papers, 75(3), 921-930. doi:10.1007/s11696-020-01352-6

Wamsler, C., Brink, E., & Rivera, C. (2013). Planning for climate change in urban areas: from theory to practice. Journal of Cleaner Production, 50, 68-81. doi:https://doi.org/10.1016/j.jclepro.2012.12.008

Wang, S., Wang, W., & Yang, H. (2018). Comparison of Product Carbon Footprint Protocols: Case Study on Medium-Density Fiberboard in China. International Journal of Environmental Research and Public Health, 15(10), 2060. doi:10.3390/ijerph15102060

Wojtacha-Rychter, K., Kucharski, P., & Smolinski, A. (2021). Conventional and Alternative Sources of Thermal Energy in the Production of Cement—An Impact on CO2 Emission. Energies, 14.
Zhengang, Z., Weerasiri, R., & Dissanayake, D. (2011). *Attitudes, Awareness and Environmental Management Practices of Small and Medium Sized Enterprises (SMEs) in Sri Lanka.*