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Review Article

An Overview of the Utilization of Common Waste as an Alternative Fuel in the Cement Industry

Tee How Tan[1], **Kim Hung Mo**[2,3], **Jiayi Lin**[2] and **Chiu Chuen Onn**[2,3]

[1]*Department of Construction Management, Faculty of Built Environment, Tunku Abdul Rahman University of Management and Technology, Kuala Lumpur 53300, Malaysia*
[2]*Department of Civil Engineering, Faculty of Engineering, Universiti Malaya, Kuala Lumpur 50603, Malaysia*
[3]*Centre for Transportation Research, Faculty of Engineering, Universiti Malaya, Kuala Lumpur 50603, Malaysia*

Correspondence should be addressed to Tee How Tan; austintee28@gmail.com

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As concrete is one of the most commonly used construction materials, there is a massive production of cement, which causes cement manufacturing to be an energy-intensive industry. A significant amount of the cost of cement production, ranging from 20% to 25%, is attributed to thermal energy. In addition, the action of mining and burning fossil fuels results in the unfavorable emission of hazardous compounds into the environment. Therefore, the switch from conventional fossil fuels to alternative fuels (AFs) in the cement manufacturing business has attracted attention due to environmental and financial concerns. In this paper, four commonly used AFs are discussed, which are waste tires, municipal solid waste, meat and bone meal, and sewage sludge. It is found that each AF has a unique calorific value and properties, attributed to its source, treatment, and technology. Furthermore, the availability of AF is important as the amount varies depending on the location. In addition, their effects on gaseous emissions from the cement plant and the quality of clinker are found to be inconsistent. Thus, there will not be a single best type of AF option to be used in the cement industry. A good AF should be able to provide sufficient thermal energy while reducing the environmental impacts and costs. A careful analysis and multicriteria decision-making approach are always vital when employing AFs in order to prevent environmental problems, cost increases, as well as clinker quality degradation.

1. Introduction

Cement is ranked as the second-most consumed material globally [1]. However, the cement industry has long been associated with high CO_2 emissions. The cement industry accounts for approximately 8% of global anthropogenic CO_2 emissions [2, 3]. It is reported that to manufacture 1 ton of cement, approximately 1 ton of CO_2 is emitted [4]. In addition to the enormous CO_2 emissions, cement production greatly depletes natural resources, including fossil fuels. Therefore, the cement manufacturing industry is under increasing pressure from environmental protection agencies to reduce its CO_2 emissions and to employ sustainable resources.

In response to the challenges, several approaches have been implemented to reduce CO_2 emissions as well as to preserve natural resources. Carbon capture, utilization, and storage (CCUS) technology in cement production has become an attractive and active research area. Korczak et al. [5] reviewed the available technologies in decarbonization of the nonmetallic minerals industry in the European Union (EU), including the cement industry, and found that CCUS has the highest decarbonization potential, up to 60%. However, impurities such as sulfur oxide (SO_x), nitrogen oxide (NO_x), and carbon monoxide (CO) are present in significant amounts in the cement kiln flue gases [6], complicating the capture of pure CO_2. Another approach is to reduce the demand for cement by replacing cement in the concrete composition, particularly using supplementary cementitious materials, alkali-activated materials (AAM), or geopolymer. However, the relatively new nonportland binders lack building codes and data on their long-term durability, which increases the demand for the development of realistic accelerated tests and careful analysis of field performance. Nevertheless, due to the long lead times required for the completion of such tests, portland cement will likely continue to be the primary material for several decades [4]. Thus, lowering the clinker-to-cement ratio [7] is considered the best approach due to its maturity and can be adopted immediately by almost all of the worldwide cement manufacturing plants.

A large amount of nonrenewable natural fossil fuels, such as coal, has been consumed each year to manufacture cement. To manufacture 1 ton of cement, approximately 1.5 ton of raw materials, 3,000–4,300 MJ of fuel energy, and 120–160 kW hr of electrical energy are required [8]. Nevertheless, the supply of coal is predicted to be in short supply in the near future in order to achieve the goal of halving CO_2 emissions by 2030 and reaching net zero emissions by 2050. On top of that, the cement industry is very vulnerable to fuel price fluctuations [9]. As a result of the energy-intensive characteristics of cement production processes, escalating fuel prices, and fuel shortages, the cement industry is forced to search for alternative fuel (AF) sources [9–11]. Adopting wastes as an AF in the cement industry is another viable approach to reduce CO_2 emissions and preserve natural fossil fuel, as well as cost savings. AF utilization has begun in the mid-1980s [12]. In 2014, AF accounted for 16.4% of total thermal energy demand in Japan. In 2015, AF contributed 64.6% of the total thermal energy demand in Germany's cement industry [13].

Although energy recovery is ranked fourth in the waste management hierarchy, it has seen a significant increase in interest in recent decades as a means of reusing waste or byproducts rather than dumping them. This is due to the fact that prevention, reduction, and recycling are impossible to always be executed, especially when dealing with matters that are closely related to human-needed activities, such as transportation, treatment of wastewater, and more. Thus, in those scenarios, coprocessing becomes the logical first response to the issue of disposal since the solution can be implemented immediately [14]. The use of waste (both industrial and agricultural) as AF reduces the burden on landfills as well as the operational costs of the cement manufacturing industry [15]. In addition, there are several notable factors that promote the use of wastes as an AF in the cement kiln, such as the high temperatures of the cement kiln, the appropriate length of the kiln, the long amount of time the fuel is kept within the kiln, and the alkaline environment within the kiln. All of these would ensure that the use of wastes as an AF is ecologically safe [11].

The objective of this work is to give an insight into the application of wastes as AF in the cement industry, including their possible impacts on the quality of cement as well as the environment. In general, depending on local availability and energy performance, a wide range of AFs can be used in the cement industry. Nevertheless, in this work, only four solid-based AF are chosen, namely waste tires, sewage sludge (SS), refused-derived fuel (RDF), and meat and bone meal (MBM), attributed to the aim of this work is to provide an implication of AF utilization in the cement industry. These four wastes are chosen due to their widespread application as an AF in the cement industry [16]. Another important reason is due to their abundance, as these wastes are generated by highly necessary human-related activities, such as vehicle use, treatment of wastewater, disposal of municipal solid waste (MSW), slaughtering of animals for food, and so forth. Hence, management of these wastes is more alarming and recovery of energy from these wastes is a viable approach. In this work, the potential of these wastes as an AF in the cement industry is discussed, covering the calorific value and their potential impacts on cement and the environment. A brief comparison of these fuels has been included which could be useful for experts from the AF application and cement industry.

2. Cement

Figure 1 presents the global cement production from 2010 to 2022. Since 2010, the global cement production has increased significantly. Although the rate of usage of other building materials, such as wood [20] and alternative binder materials such as AAM or geopolymer has increased, the demand for cement globally is anticipated to keep rising. This is largely due to the rapid development of a few countries, such as China. The cement production in China is estimated to be around 2,400 Mt, which is approximately 57% of the world cement production [18, 20]. On the other hand, cement production is technologically mature and widely accepted. Nevertheless, the global cement production in 2022 is estimated to reduce to 4,100 Mt as compared to the global cement production in 2021 which is estimated at 4,400 Mt. This is due to the reduction in the cement production of China in 2022, which is from 2,400 to 2,100 Mt [21], probably due to the implementation of the long period lockdown policy during the COVID-19 pandemic. As a result, it is therefore anticipated that the associated environmental pollution and depletion of natural resources from the cement industry will continue to occur in the absence of suitable intervention.

2.1. Energy Consumption. The average energy demand for producing 1 ton of cement is around 3.3 GJ of thermal energy, which equates to 120 kg of coal with a calorific value of 27.5 MJ/kg and roughly 110 kW hr/t of electrical energy [10, 22, 23]. Burning operations employ the majority of the thermal energy, whereas cement grinding utilizes the electrical energy [24, 25]. According to Oggioni et al. [26], for each ton of cement produced, energy expenditures in the form of fuel and electricity account for 40% of the total production costs. Thus, besides promoting sustainability, replacing fossil fuel with AF will help to lower the energy costs and, consequently, the production costs, giving the cement plant using this form of energy a significant advantage.

The energy efficiency of cement plants is also significantly influenced by the type of cement kiln utilized. Since the 1970s, initiatives have been made to optimize a cement kiln's energy efficiency [27], in which the cement kiln has evolved from the lengthy wet kiln to a cutting-edge dry kiln that is equipped with calciners, six-stage preheaters, and high-efficiency coolers [28]. Because of this, the total amount of energy used has gone down from 6 to around 3 $GJ/t_{clinker}$ [29–32].

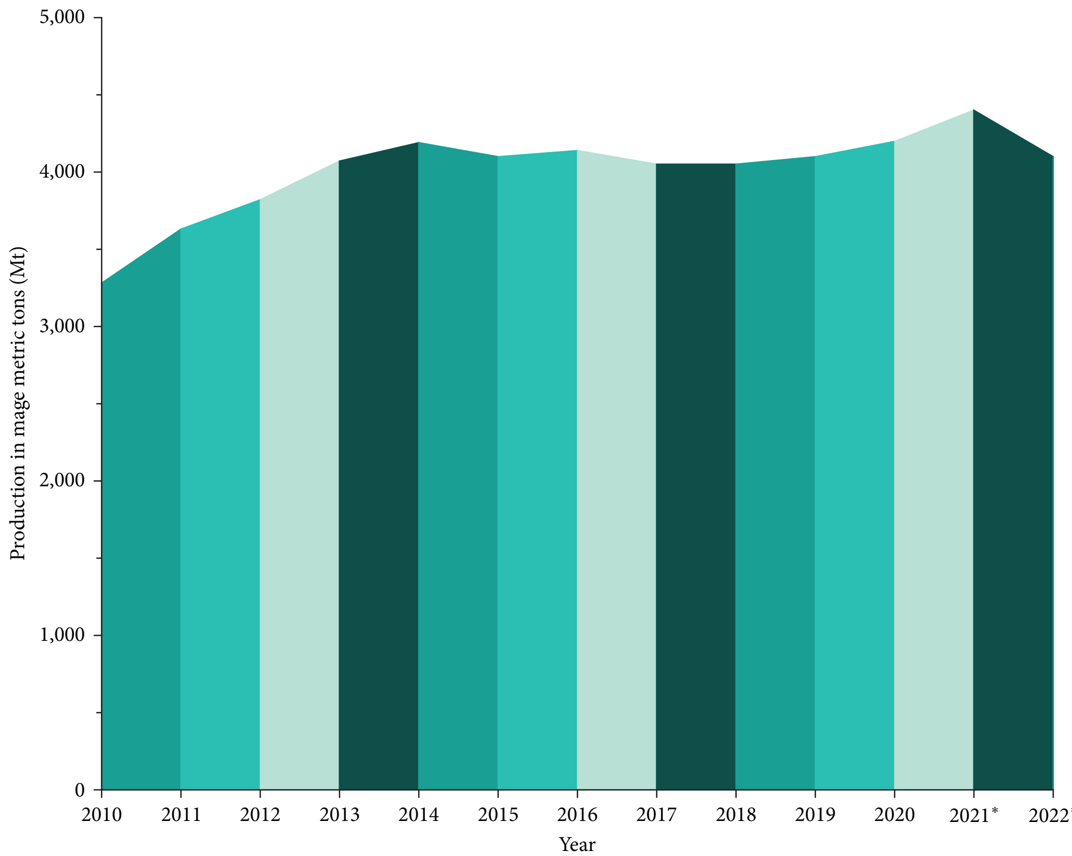

FIGURE 1: Global cement production from 2010 to 2022 [17-19]. * = estimated value.

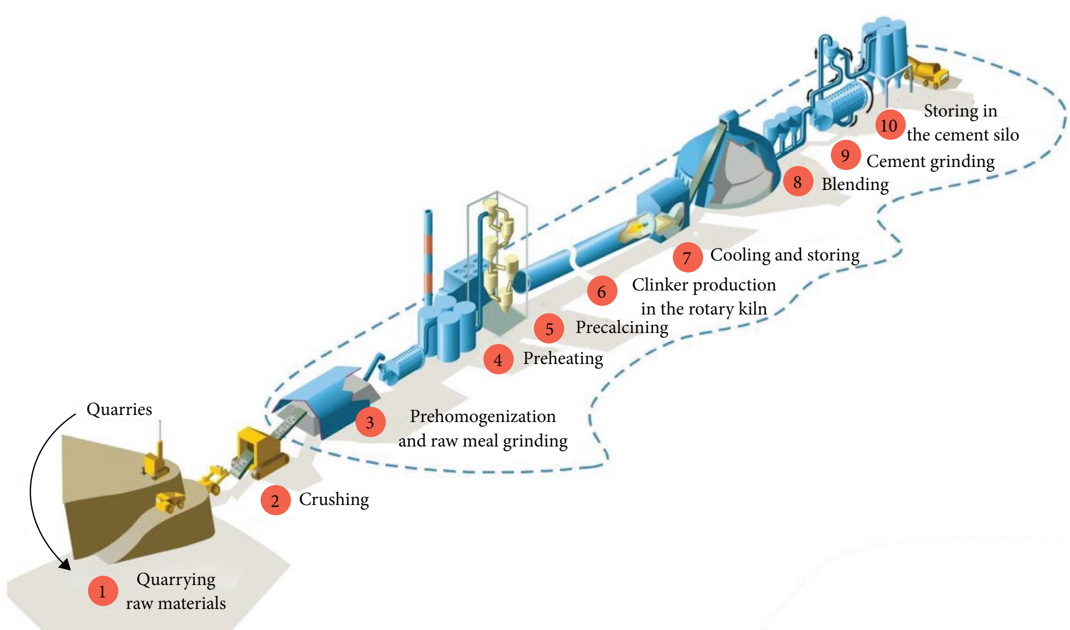

FIGURE 2: Dry kiln cement manufacturing process [33].

The cement manufacturing process in a dry kiln is shown in Figure 2. The three primary stages of the cement manufacturing process include the preparation of raw materials, clinker production, and cement manufacturing. First, raw meal, a homogeneous mixture made by combining and milling several raw materials, is obtained. The raw meal is then preheated, precalcined, followed by calcination in a high-temperature rotary kiln, typically operating at 1,450°C, to produce clinker.

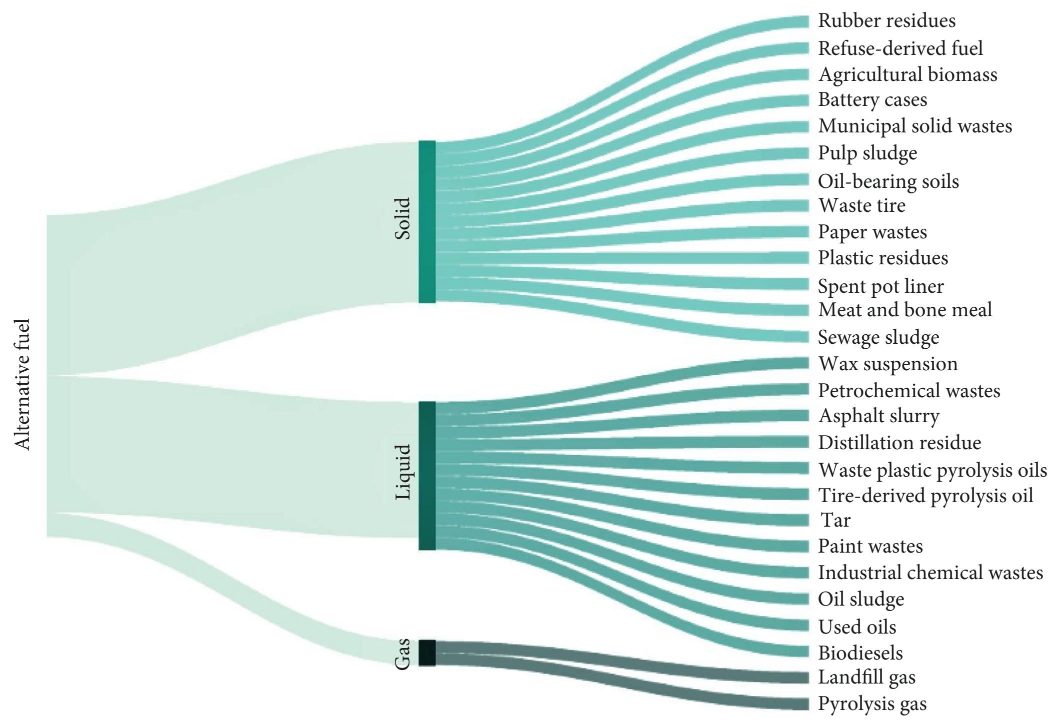

Figure 3: AF options for the cement industry.

Finally, the clinker is cooled, ground, and blended with gypsum to form cement. At this stage, additional cementitious ingredients, such as fly ash, may be added to produce blended cement. The grinding and blending processes can be done onsite at the kiln or at a separate grinding or blending facility.

2.2. CO_2 Emissions. The CO_2 emissions from the cement industry can be divided into three parts, which are process-related CO_2 emissions, fuel-related CO_2 emissions, and electricity-related CO_2 emissions. The process-related CO_2 emissions generally involve the decomposition of raw materials, for instance, limestone, during the clinker calcination stage. The fuel-related CO_2 emissions are directly associated with the combustion of fuel. The typical calcination temperature in the cement kiln reaches 1,450°C, which requires a large number of fuels. The electricity-related CO_2 emissions come from the consumption of electricity to run the cement plants, such as mills, fans, and other electrical equipment that are powered by electricity [34]. About 50% of the total CO_2 emissions in the cement manufacturing process are due to process-related CO_2 emissions, while fuel and electricity-related emissions account for the remaining 40% and 10% of emissions, respectively [16, 35].

3. Alternative Fuel

AF refers to materials other than conventional fuels such as fossil fuels that can be adopted to recover thermal energy, including waste materials [36]. Figure 3 presents some of the AF that can be employed in the cement manufacturing industry, based on their physical state [37]. The AF are classified into three basic groups, which are gas, liquid, and solid [11]. Nevertheless, there are hundreds, if not thousands, of AF that can actually be used in cement plants [38] and further exploration is needed. For instance, pyrolysis oil derived from waste plastics (WPPO), which is a viable option due to waste plastics have always been a global issue [39, 40], biodiesels that can be derived from various sources, such as waste coconut, sunflower, and palm cooking oils [41] as well as pyrolysis oil derived from waste tires [42].

Every AF, even of the same type, is unique and has distinctive properties depending on the region, technology, and the route of the waste produced. BS EN ISO 21640 classifies the AF, particularly solid recovered fuels, into five classes based on their net calorific value, chlorine content, and mercury content. Thorough examination and consideration are essential during the AF selection process. A multicriteria decision-making (MCDM) method is generally employed in the selection process [43, 44]. This is because, in addition to calorific values, the effects of AF on cement, the environment, operational costs, and so forth are significant. The following traits are likely to be taken into account during AF selection [11, 24]:

(i) Physical state of the fuel (solid, liquid, and gaseous)
(ii) Content of circulating elements (Na, K, Cl, and S)
(iii) Toxicity (organic compounds and heavy metals)

(iv) Composition and content of ash
(v) Content of volatiles
(vi) Calorific value (>14.0 MJ/kg)
(vii) Chlorine (Cl) content (<0.2%)
(viii) Sulfur content (<2.5%)
(ix) Polychlorinated Biphenyls (PCBs) content (<50 ppm)
(x) Heavy metals content (<2,500 ppm) (out of which: mercury (Hg) <10 ppm, and total cadmium (Cd), thallium (Tl), and Hg < 100 ppm)
(xi) Physical properties (size, density, and homogeneity)
(xii) Grinding properties
(xiii) Moisture content
(xiv) Proportioning technology
(xv) The emissions
(xvi) The cement quality and its compatibility with the environment must not decrease
(xvii) AF must be economically viable
(xviii) Availability of the AF.

3.1. Type of Alternative Fuel

3.1.1. Waste Tire. Waste tire is a waste that originates from the automobile industry, and it has become much more prevalent since vehicles are such a dominant mode of mobility. Around 3 billion tires are traded commercially around the globe each year, and an equivalent number are discarded when they no longer serve a purpose [45]. The United States of America, Japan, and the EU discard about 5 million tonnes of tires annually [15]. The billions of tires that are already stockpiled or buried in landfills, warehouses, and illegal sites will continue to grow over time, and they are prone to environmental threats, including becoming home to rodents and insects [38].

About 70% of the total waste tires at the end of their service life is recycled, with the majority of them converted to fuel or used for the production of various materials [45]. In the mid-1980s, waste tires became a popular AF option for the cement industry, attributed to the spike in fossil fuel prices and high calorific value [14]. According to several studies, the net calorific value of waste tires is about 27–37 MJ/kg, and they burn quickly [1, 9, 32, 46]. Tire is composed of about 88% carbon and oxygen, and its total annihilation is guaranteed at temperatures above 800°C and with gas retention at high temperatures. Complete destruction will prevent the formation of intermediate products of incomplete combustion, such as black smoke and odors [1]. Thus, the use of waste tires as AF in the cement industry has gained popularity, owing to the high temperature during calcination (1,450°C), long retention time, and alkaline environment inside the kiln [1]. In addition, a tipping fee will be provided for collecting the waste tires, which will help to offset the transportation costs. Castañón et al. [9] reported that the annual fuel cost to manufacture clinker using pure petcoke was around 8,000,000 €/year, while using 40% waste tires as AF would cost only 5,938,000 €/year.

Figure 4: Waste tires [49].

Table 1: Calorific value of waste tires.

Reference	Calorific value (MJ/kg)
[37]	35.50
[51]	37.10
[52]	31.00
[53]	31.40
[54]	31.80
[1]	27.00
[55]	31.40
[56]	31.88
[9]	29.71

Utilization of waste tires as AF helps to reduce the consumption of nonrenewable fossil fuels and conserve natural resources [47]. Meanwhile, the environmental impacts due to the disposal of waste tires can be minimized. According to Fiksel et al. [48], the use of waste tire as AF in cement manufacturing plants provides more reduction in most environmental impact categories compared to other waste tires applications, after the application of artificial turf.

The waste tires can be burned as a whole or in the form of shredded and fine-grained, depending on the combustion unit, and is known as tire-derived fuel. Figure 4 shows the photos of waste tires. According to the United States Environmental Protection Agency [50], waste tires produce the same amount of energy as oil and 25% more energy than coal. Table 1 presents the calorific value of waste tires reported in the literature. On the other hand, the waste tires exhibit low moisture content and high carbon content, and the reinforced wire of the tire can be consumed as an iron source when the whole tire is burned [14, 37].

(1) Impacts of Waste Tires as AF to Cement and Environment. According to Castañón et al. [9] and Nakomcic-Smaragdakis et al. [1], the clinker quality was maintained when waste tires were used as AF. No significant variation in the clinker content, in terms of alite (C_3S) and free lime, was observed when using waste tires as AF; the C_3S content of the clinker was higher than 70%, while the free lime content was less than 2.5%. A similar observation was reported by Puertas and Blanco-Varela [57], where a comparable clinker mineralogical composition was obtained when waste shredded tires were used as AF. This is probably due to the amount of waste tire ash that incorporates into the clinker is considerably low, thus the effect is small or negligible. According to Czajczyńska et al. [58], the

Table 2: Chemical composition of waste tires ash [59].

Compound	Composition (%)
CaO	47.0
SiO_2	14.1
Al_2O_3	2.7
Fe_2O_3	1.1
Na_2O	<0.01
K_2O	<0.01
MgO	0.7
TiO_2	<0.01
P_2O_5	<0.01
SO_3	1.2
MnO	<0.01
ZnO	33.1

amount of waste tire ash produced after incineration is around 7%. In addition, another possible reason is due to the composition of waste tire ash, as shown in Table 2. It is observed that the main constituent of waste tire ash is reported to be CaO, SiO_2, and ZnO, while CaO and SiO_2 are the vital components for clinker formation.

Nonetheless, it has been established that the usage of waste tires as AF in the cement industry leaves no residue behind as the slag and ashes would be incorporated into the clinker during the calcination process. Table 2 depicts the waste tire ash, reported by Mónica et al. [59], which possesses a high ZnO content of up to 33.1%. This is attributed to Zn being often used in the tire-making process to enhance the vulcanization process. Thus, when waste tires are combusted in the cement kiln, the residue ash is anticipated to be incorporated into the clinker, and resulting in the increment of the ZnO level of the clinker. For instance, a high zinc (Zn) content, compared to conventional clinker, was observed in the clinker produced with shredded tires as an AF [57].

The incorporation of Zn during the clinkering process usually results in a reduced quality cement product with prolonged setting time and lower strength [36, 46] due to the diminishing or even disappearance of C_3A when the amount of Zn that is incorporated during the clinkering process has exceeded the threshold limit; typical Zn concentration in OPC is far from the threshold limit. In addition, a new product, $Ca_6Zn_3Al_4O_{15}$ may formed [60]. Mónica et al. [59] investigated the effect of waste tire ash (Table 2) as an additive to the clinker. The 28-day strength of the clinker produced with the addition of 30% of waste tire ash shows only a slight reduction compared to the control cement sample, which was approximately 45 and 50 MPa, respectively. Soto-Felix et al. [61] studied the effect of ZnO as an additive on the setting time and strength of cement. The results showed that adding ZnO to the cement increased the setting time and decreased the strength. Slight strength improvement was observed when a very low content of ZnO was added due to the filler effect. Therefore, due to the elevated Zn content in the clinker, the use of waste tires as AF in the cement industry is suggested to be limited to a maximum of 30% [1] to prevent the significant reduction of C_3A content and formation of $Ca_6Zn_3Al_4O_{15}$ that results in quality degraded cement product.

Table 3: Gaseous emissions with waste tires as AF.

Reference	SO_2	NO_x	Dioxin	Furan
[63]	–	Decreased	–	–
[64]	Increased	Decreased	Decreased	Decreased
[65]	Increased	Increased	Unchanged	Unchanged
[66]	–	–	Increased	Increased
[54]	Increased	Increased	–	–
[1]	Fluctuated	Fluctuated	–	–
[62]	Increased	Unchanged	–	–
[9]	Decreased	Decreased	–	–

On the other hand, Castañón et al. [9] compared the gaseous emissions when 100% petcoke fuel and a 6 : 4 fuel mix comprised of petcoke and waste tires are used. It is reported that when 40% of waste tires were employed, the NO_x and sulfur dioxide (SO_2) emissions were decreased by 17% and 28%, respectively. The reduction is highly related to the reduction of sintering temperature, lower oxygen content as well as lower sulfur content in the waste tires compared to petcoke. The sulfur content of waste tires and petcoke was around 1.3% and 6%, respectively. However, the SO_2 emissions were found to have increased in some cases, which may be due to the fact that the employed fuel is coal. Coal has a lower sulfur content compared to petcoke, which is 2.45% [62]. Another possible reason could be the incomplete combustion of waste tires [1]. Thus, the gaseous emissions are found to vary, which is believed due to the adoption of different fuels, variation in the composition of the waste tires as well as their substitution level. The SO_2, NO_x, dioxin, and furan emissions when using waste tires as an AF are tabulated in Table 3.

3.1.2. Municipal Solid Waste. Around 440 kg of MSW is produced globally per person per year [67]. MSW is typically disposed of in a sanitary landfill. However, as a result of the growing human population's impact on the amount of MSW produced and the diminishing volume of landfill space, managing MSW has turned into a significant problem. In some cases, MSW is simply dumped in open dumping areas, posing health and environmental risks such as foul odor, methane emission, soil pollution, as well as groundwater pollution caused by leachate from landfilled waste. Therefore, demand for alternative MSW treatment methods that can effectively reduce the volume of MSW while avoiding or minimizing the associated negative impacts is arising.

In the waste management hierarchy, top priority is given to waste prevention, followed by reuse, recycling, recovery, and disposal [68]. However, the first three stages may be difficult to carry out at all times; thus, energy recovery through incineration is the best solution [69]. MSW incineration possesses several benefits, such as significant volume reduction (~70%–90%), recovering energy, and eliminating pathogens [21, 67, 70]. Nevertheless, direct MSW incineration in the cement industry sometimes incurs operational issues such as incomplete combustion, increased specific

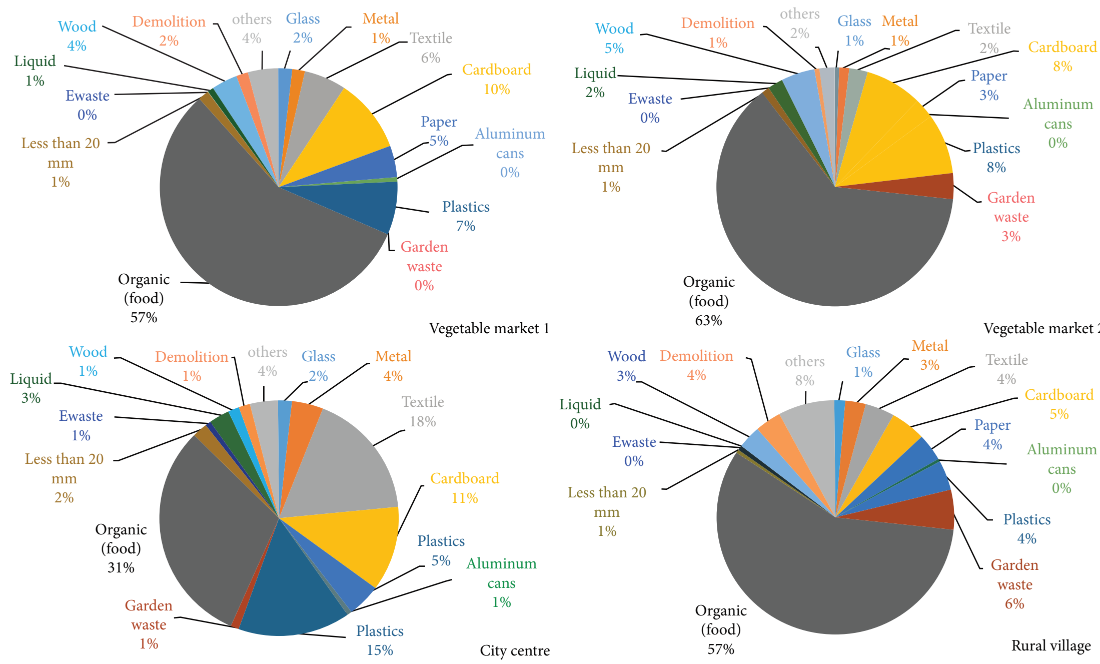

FIGURE 5: MSW composition at different sources in Irbin City, Jordan [49].

heat consumption, lower flame temperatures, and kiln coating buildup [71]. This results in the increased interest in gasification technology [67, 71]. Nevertheless, since the aim of this work is to provide an overview of the common wastes that can be used in AF in the cement industry, only the combustion technology is discussed here.

Due to cultural differences and the level of source separation, recycling, and processing, the composition of MSW varies significantly from one country to another. Figure 5 shows the MSW composition at Irbid City, Jordan [49]. Even in the same city, the MSW composition varies due to different sources. Therefore, most of the cement plants do not directly employ and burn the unsorted MSW due to its heterogeneous nature [16] that will lead to an inconsistence combustion performance. On top of that, untreated MSW usually exhibits low calorific value, high moisture content, and contains undesired components such as noncombustible compounds that will decrease the calorific value. Generally, the calorific value of MSW is around 6.21 to 9.2 MJ/kg [72, 73].

Considering the low calorific value, higher moisture, and ash content of MSW, RDF (Figure 6) is typically employed. RDF is an AF that is obtained after the removal or rejection of noncombustible materials from the MSW, for instance, ferrous materials, grit, and glass [70]. Removing metals during the sorting process would reduce the heavy metal content in the RDF [75]. RDF made from MSW has constant thermal and energetic characteristics, a low level of pollutants as well as a high calorific value [72]. The main steps involved in producing RDF from MSW typically involve preliminary liberation, size screening, shredding, magnetic separation, and pelletizing [14]. Various RDF forms are available, including fluff, pellets, bricks, or logs [76].

FIGURE 6: RDF in pellet form [74].

Table 4 presents the composition of RDF produced from MSW as investigated by Kara [77]; the main components of RDF are PET plastic, paper, plastic bags, and textiles. Nonetheless, the composition of RDF and its calorific value can vary between places [78]. The RDF formulated by Zhao et al. [79] consists of 42% plastics, 41% paper or cardboard, 7% textiles, and 10% horticultural waste, based on Singapore's waste composition. The net calorific value of the RDF was higher than that of Kara [77], which may be attributed to the variation in RDF composition. Furthermore, when Zhao et al. [79] included chicken manure and biomass waste into the formulation of RDF, the moisture content of RDF significantly increased from 7.8% up to 23.8% while the net calorific value dropped from 23.7 to 16.1 MJ/kg. Hence, this proves that the regional variations of MSW composition,

Table 4: The composition of MSW and RDF [77].

Content	Input: MSW (%)	Output: RDF (%)
Textile	17.1	66.0
Paper	25.4	17.1
Organic fraction	22	0
Plastic bag	15.2	13.3
Napkin	7.0	0
Other combustible	3.7	0
PET-plastic	3.2	3.6
Wood	1.9	0
Bone	0.3	0
Tetrapac	1.2	0
Sack	0.5	0
Tin	0.6	0
Glass	0.7	0
Aluminum	0.4	0
Stone	0.8	0
Total	100	100

Table 5: Calorific value of RDF.

Reference	Calorific value (MJ/kg)
[80]	12.00–2100
[81]	12.69
[51]	19.90
[70]	14.64
[82]	19.40
[83]	19.67
[84]	17.79
[79]	16.10–23.70
[85]	14.90
[86]	25.02
[72]	15.21
[87]	29.11
[88]	15.97
[89]	17.90
[90]	26.82–29.26

technology level, equipment, and formulation would influence the performance of RDF. Table 5 shows the varied calorific values of the RDF, ranging from around 12.00 to 23.70 MJ/kg. The calorific value of RDF, in general, is higher than the calorific value of MSW.

(1) Impact of MSW as AF to Cement and Environment. Kara et al. [70] examined the potential of RDF made from MSW as an AF in cement manufacturing in Istanbul, Turkey. The RDF is composed of 66% textiles, 17.1% paper, 13.3% plastic bags, and 3.6% PET plastic. The RDF was mixed with the main fuel at a ratio in the range of 0%–20% to produce clinker, and the outcomes indicated that clinker produced with 20% RDF was satisfactory. However, when the proportion of RDF was increased, the C_3S content of the clinker was decreased (max. 5%) while belite (C_2S) content was increased (max. 3%). However, Haračić et al. [90] reported C_3S content of clinker was increased by 2% while C_2S content decreased by 2%. This is probably due to the variation in the quality of RDF used, which is clearly indicated by the difference in calorific value of the two RDF used (Table 5). In addition, the humidity of the RDF used by Kara et al. [70] was 25%, which is higher than the RDF of Haračić et al. [90], 17.5%. Thus, it can be suggested that the variation in the clinker composition is highly due to the quality of the RDF, particularly the humidity, that influences the clinker calcination process.

On the other hand, there is a concern when using RDF as AF in the cement kiln, namely its high chlorine content that would be deleterious to the concrete [70, 77, 91]. The chlorine content of the RDF investigated by Kara et al. [70] was reported to be 0.95%. On the other hand, Özkan et al. [92] reported that the chlorine content of the RDF can be up to 1.41% while Hemidat et al. [72] stated that the chlorine content in RDF varied from 00.56% to 1.20%. The chlorine content is possibly due to the presence of plastic material in the mixture. In addition, high chlorine content could be a risk to the cement kiln as chlorine-based salts are highly volatile under the cement kiln condition, thus being the major driver of the formation of coatings and cloggings in the preheater [86]. A similar observation was observed by a waste-to-energy plant in Chengdu, China where the superheater steel tubes were corroded [91].

In 1977, the existence of dioxins were found in the emission and fly ash of a RDF incineration plant [93]. Considering the high chlorine content possessed by RDF, the effect of MSW, or particularly the RDF, adoption in cement plant toward the environment requires great attention. This is due to it is considered a source of acidic contaminants and reactive components to create dioxins [94]. In general, the adoption of MSW or RDF as AF in the cement industry delivers promising environmental benefits. Sai Kishan et al. [14] reported that the effluent gas from the mixed fuel showed a reduction in the content of SO_x, NO_x, and polycyclic aromatic hydrocarbon (PAH) content. Kara [77] also indicated that the amount of NO_x, gaseous heavy metals as well as dioxins and furans decreased with an increasing amount of RDF. This could be the high temperature in the cement kiln that encourages the formation of new minerals between the chlorine and other elements in the raw meals that avoiding dioxins formation [93]. In addition, the high temperature and long retention time of the cement kiln system aids in completely breaking down the harmful substances possessed by RDF.

3.1.3. Sewage Sludge. SS is a by-product of wastewater treatment, and management of SS has grown increasingly difficult over the years. This is due to the fact that besides containing high organic and mineral content, high water content, and the ability to rot, the SS contains toxic substances such as heavy metals, PAHs, PCBs, and dioxin [95], which are deemed harmful to human being and the environment. Besides that, due to the high volume of wastewater being treated, the volume of SS generated spikes up; the volume of SS generated is reported to be approximately 3% of the volume of treated wastewater [96]. Thus, the disposal of SS

Figure 7: Dewatered SS [96].

Table 6: Proximate analysis of dewatered SS [100].

Component	Raw SS (%)
Moisture	80
Ash	9.1
Volatile matter	10.1
Fixed carbon	0.8

has become a major waste management issue in response to worries about landfill space and the buildup of heavy metals or pathogenic organisms in soils [1, 97]. Furthermore, to treat and manage the SS properly that meets the environmental requirements, the cost could be as much as 50% of the operational cost of the wastewater treatment plant [95].

Considering the harmful effects, high treatment cost, and large volume of SS, the necessity to employ another treatment method is in high demand. The most commonly adopted technique of SS management is in agriculture, where the SS works as a fertilizer. Nonetheless, enforcement of legislation reducing such application, which is attributed to the presence of heavy metals and pathogenic microorganisms in SS that would become a significant problem for the soil and groundwater [96, 98]. Adoption of SS as an AF in the cement industry has been investigated and proved feasible, attributed to its calorific energy potential [99] and the high incineration temperatures in the cement kiln can sufficiently destroy the potentially dangerous compounds and substances possessed by SS, making it an appropriate method of handling SS.

Since SS is made up of water and organic matter in the form of fine-grained solid suspensions or colloids, the raw SS typically contains a significant volume of water [14, 15, 96]. Regardless of the sludge disposal method, the SS is often mechanically dewatered (Figure 7). Table 6 depicts the proximate analysis of dewatered SS from a municipal wastewater treatment plant located in Beijing, China [100]. Although the SS is dewatered, it still contains a substantially high moisture content of around 80%. Such high moisture content usually leads to a significantly low calorific value. The calorific value of dewatered SS reported by Liu et al. [100] was around 2.43 MJ/kg. A similar outcome has been reported by Rećko

Table 7: Calorific value of dried SS.

Reference	Calorific value (MJ/kg)
[37]	15.80
[103]	14.80
[101]	8.30
[104]	10.70–13.00
[105]	12.60
[106]	15.60
[107]	10.73
[108]	14.40–14.60
[86]	14.94–17.72

[96], where the calorific value of municipal SS was only 0.89 MJ/kg when the moisture content is about 80.22%. Thus, dewatered SS, or raw SS, is not suitable for the AF application due to its extremely low calorific value caused by the high moisture content.

When dewatered SS is used as a fuel source in the cement industry, coal consumption will increase. This accounts for the extra energy required to evaporate the moisture in the dewatered SS [100]. Therefore, to adopt SS as an AF source, thermally drying the dewatered SS is a must [101], or the dewatered SS needs to be mixed with other fuels. This is because the calorific value of SS is highly dependent on the degree of dryness as well as the content of organic dry matter [96]. Thus, drying of SS can increases its calorific value [102]. According to Husillos Rodríguez et al. [101], the solid content of dewatered SS increased from 25% to 93% after the thermal drying process; higher solid content generally leads to higher calorific value. On the other hand, dried SS might be introduced into the cement kiln using the same feeding technology employed on pulverized coal due to its being a free-flowing powder [101], hence the additional cost and complexity on the new feeding route could be resolved. Nevertheless, even though extra energy is needed to dry the SS, the associated benefits of resolving the troublesome SS disposal issue and the manufacture of a sustainable fuel should be taken into consideration [101]. The calorific value of various dried SS is listed in Table 7.

(1) Impact of SS as AF to Cement and Environment. According to several investigations [100, 102, 109], the adoption of SS as AF has no detrimental effects on the clinker quality. Nonetheless, other compounds contained in the SS have the potential to migrate into the clinker as the ashes will be absorbed into the clinker during calcination. Sobik-Szołtysek and Wystalska [102] stated that the degree of clinker contamination following the use of SS as AF can rise or fall depending on the substances' concentration.

Husillos Rodríguez et al. [101] investigated the effect of thermally dried SS as an AF on portland cement clinker production. As the dried SS was mostly made of combustible organic matter (56% by mass), the remaining inorganic matter would stay as ashes and be incorporated into the clinker upon burning [101]. The high P_2O_5 content in the employed SS (Table 8) may be problematic as it is believed to influence the quality of the clinker. A similar composition is reported

Table 8: Chemical composition of dried SS [101].

SiO_2	Al_2O_3	CaO	MgO	MnO	P_2O_5	K_2O	TiO_2	LOI*
3.72	2.56	7.62	0.60	0.05	6.43	0.53	0.23	66.45

*Loss on ignition at 1,000°C.

Table 9: Chemical composition of cement produced with dried SS as AF [101].

Cement	Content (%)									
	SiO_2	Al_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cl	P_2O_5	f-CaO
With SS	21.01	5.30	66.10	1.51	0.18	0.22	0.41	0.08	1.66	2.64
Without SS	20.38	4.78	65.10	1.42	0.02	0.08	0.36	0.00	0.04	0.95

by Lopes et al. [81], where the P_2O_5, sulfur, and nitrogen contents were 21.7%, 1.34%, and 4.6%, respectively.

Table 9 compares the chemical composition of the cement produced when dried SS was used as AF. The chemical composition of the manufactured cement has not changed significantly, except for the SO_3, P_2O_5, and free lime content. This proves that the ashes have been incorporated into the clinker. According to Staněk and Sulovský [110], at 0.7 wt% of P_2O_5, diminished C_3S content had been observed. C_3S formation was found to be completely suppressed at 4.5 wt% of P_2O_5, even after a 4 hr, 1,450°C clinkering process. This is possibly due to the effect of phosphorus on the α H orthorhombic polymorph of C_2S, which delays the crystallization of C_3S and affects its crystal size as well as reduces the viscosity of the melt phases [110, 111]. Therefore, when dried SS was used as an AF, a higher free lime content (Table 9) and a reduction of the C_3S/C_2S ratio from 7.7 to 3.3 have been reported by Husillos Rodríguez et al. [101]. Similar outcomes have been reported in the work of Kwon et al. [112] and Lin et al. [113]. In addition, the cement's initial and final setting times are increased when SS has been cocombusted. When SS was utilized as AF, the initial and final setting increased from 103 to 123 and 140 to 158 min, respectively [109]. Another study carried out by Lin et al. [113] indicates that clinker with a P_2O_5 content of 0.85% possessed extremely long initial and final setting times, which were 8.8 and 11.43 hr, respectively.

Incorporation of SS as an AF in the cement industry has been reported for its reduction in NO_x emissions [100, 109, 114]. Gu et al. [115] indicated that coprocessing of SS in a cement kiln at high temperatures and low oxygen content could yield significant NO_x reduction. On the other hand, SS was coincinerated at a cement plant in Cyprus, and the gaseous emissions were measured. The gaseous heavy metal concentrations amount to only 0.7960 mg/Nm^3, which is only 16% of the allowable limit of 5 mg/Nm^3. Zabaniotou and Theofilou [116] reported that the emission of furan and dioxin was found to be only 0.006 ng/Nm^3 when SS was used, which is also lower than the allowable concentration of 0.1 ng/Nm^3.

3.1.4. Meat and Bone Meal. MBM is created in rendering factories by combining, crushing, and cooking animal offal and bones. Nonetheless, after the discovery of bovine spongiform encephalopathy (BSE), MBM waste management has become difficult as a result of the fact that MBM residue is forbidden to be used in animal feed or disposed of in landfills [16, 117]. Thus, a safe MBM disposal approach is required to avoid pathologically transmissible infections. Since high-temperature treatments, especially those with extended residence times and ample oxygen supplies, can eradicate the BSE bacteria, thermal treatment methods like incineration or gasification have become viable alternative. Energy recovery through the use of MBM in cement plants has been widely considered as a way to improve the waste management hierarchy [118]. Table 10 shows the proximate analysis of coal and MBM. The ash produced after the MBM combustion was about 20%–30% of its original weight, indicating that a huge volume had been eliminated [119, 120]. However, it should be noted that due to MBM's high-fat content, continual feeding into a fluidized bed reactor or combustor might cause significant agglomeration in the feeding system [121]. Similar as other AF, the calorific value of MBM, as shown in Table 11, varies due to the variation in their composition.

Table 10: Proximate analysis of MBM and coal [117].

Component	MBM (%)	Coal (%)
Moisture	6.8	4.2
Ash	34.4	6.2
Volatile matter	32.7	36.6
Fixed carbon	26.1	53.0

(1) Impact of MBM as AF to the Cement and Environment. MBM, in general, exhibits a high P_2O_5 content. According to Lopes et al. [81] and Ariyaratne et al. [123], the P_2O_5 content in MBM was 35.65% and 13.00%, respectively. The high P_2O_5 content would be deleterious to the quality of clinker as it would stabilize the C_2S and hence diminish the formation of C_3S. In addition, a prolonged cement setting time is usually observed with high P_2O_5 content. On the other hand, the high calcium content in MBM could be another potential risk as it would increase the free-lime content of clinker. According to Ariyaratne et al. [123], the free-lime content in the clinker was increased from around 1.25% to 3% when the feed rate of MBM (CaO = 13.3%) was 7 t/hr, indicating an improper burning process and poorer quality of clinker.

By contrast, the calcium content is beneficial in reducing SO_2 emissions. Rahman et al. [38] claimed that the MBM's

Table 11: Calorific value of MBM.

Reference	Calorific value (MJ/kg)
[37]	16.20
[81]	14.47
[122]	18.19
[123]	18.51
[107]	17.45
[62]	30.71
[86]	17.58
[124]	18.42

high calcium concentration reduced the SO_2 emissions as it could retain most of the SO_2 formed. This is due to the ability of calcium to absorb sulfur [52]. Rahman et al. [62] reported that the SO_2 emissions were reduced from 280 to around 245 mg/Nm^3 when 30% of MBM was adopted in the fuel mix. A similar outcome has been reported by Aranda Usón et al. [16], where the SO_2 emissions with 100% MBM and 100% coal were reported to be 14 and 713 mg/Nm^3, respectively.

Nevertheless, the employment of MBM as AF could increase the NO_x emission, which is attributed to the high nitrogen content in the MBM [16]. Lopes et al. [81] and Bujak et al. [124] stated that the nitrogen content in MBM was around 8.5%. Rahman et al. [62] reported that the NO_x concentration was increased when MBM was employed in the fuel mix. With 30% of MBM, NO_x emission increased by about 9%. On the other hand, Abad et al. [125] reported that cocombustion of MBM with coal had no significant impact on the furan and dioxin emissions. To determine the effects of various MBM parameters on the coal cocombustion process, Gulyurtlu et al. [117] conducted several experiments with various MBM/coal ratios. This study revealed that increasing the MBM ratio had negligible effect on emissions, particularly those of CO and SO_2. However, because of the high nitrogen content of MBM, its use may result in an increase in NO_x emissions.

3.2. Advantages of AF in the Cement Industry. The adoption of AF in the cement manufacturing industry has several benefits. First, AF is relatively cheaper than the commonly used fossil fuels. This is because they are usually waste products that need to be managed, either disposed of at a landfill or incinerated. Thus, extra costs, in terms of environmental or operation, are incurred by this process. With the application of AF, the cost can be reduced, including the material cost, transportation cost, and incineration cost. A tipping fee will be provided for collecting the wastes. Pitak et al. [126] reported that using 10% AF as a substitute for coal fuel results in a net savings of 754.7 USD/hr. According to Trezza and Scian [127], maximum cost reduction can be achieved if the AF can be used with minimal preparation. In addition, the use of AF can preserve nonrenewable fossil fuels, which is a great benefit to the environment while offering a safe option for the disposal of wastes, particularly those that are organic or biologically hazardous, and can alleviate the landfill shortage problem. Furthermore, Horsley et al. [15] stated that it is considerably cheaper to adapt a cement kiln to incinerate the wastes instead of building a new, dedicated waste incinerator.

Another key advantage of employing AF in the cement industry is that the fuel combustion process in the cement kiln is a nonwaste process because the ashes can be incorporated into the clinker [16]. However, the incorporation of such ashes may have a certain influence on the quality of the cement, thus, a comprehensive understanding of the waste materials to be used as AF is a must. On the other hand, employing wastes as AF in the cement industry has been proven to reduce the common hazard and pollution caused by typical disposal methods like landfilling. For instance, utilization of MBM as AF can helps to eliminate the BSE bacteria. In addition, the alkaline environment in the cement kiln is an important feature for such an application. The basic environment aids in the neutralization and capture of acid gas components that are being produced during the combustion process. Furthermore, rather than being released into the atmosphere, heavy metals that condensed on dust molecules are returned to the clinker [10].

3.3. Disadvantages of AF in Cement Industry. Although full or partial conversion of the thermal energy supply from conventional fossil fuels to AF possesses several attractive benefits, several challenges are present as AF exhibits different characteristics, even of the same type, compared to conventional fossil fuels. Some of the major challenges that have been reported when using AF in the cement industry are, but not limited to, poor heat distribution, unstable precalciner operation, blockages in the preheater cyclones, and buildups in the kiln riser ducts. In some investigations, gaseous emissions such as SO_2, NO_x, and CO emissions were reported to have increased when AF was used [127], which is attributed to the composition of the respective AF. AF with higher sulfur and nitrogen content should be given more attention. The proportion of AF and the filter system of the cement kiln can also be the potential cause. Therefore, extensive investigations and monitoring are necessary due to the complexity of adopting AF in cement plants.

Another major concern of AF utilization in the cement industry is the incorporation of combustion residues, or ashes, into the clinker, which affects the clinker quality. The amount and type of ashes introduced by AF are largely different from those introduced by fossil fuels, introducing several unexpected components into the kiln [12]. Phosphorus, which is primarily found in MBM or SS, is a notable example. The performance of cement may be affected by the presence of phosphorus, such as decreased early strength or prolonged setting times [128]. Besides that, higher free-lime content may be observed in the clinker when AF with high phosphorus and calcium content is adopted. As a result, if the quality of a clinker is compromised, the benefits of AF utilization may be negated.

Switching to AF is sometimes detrimental to the production cost at the initial stage (conversion process), which accounts for the investment costs associated with the adjustment or replacement of the burner, implementation of the

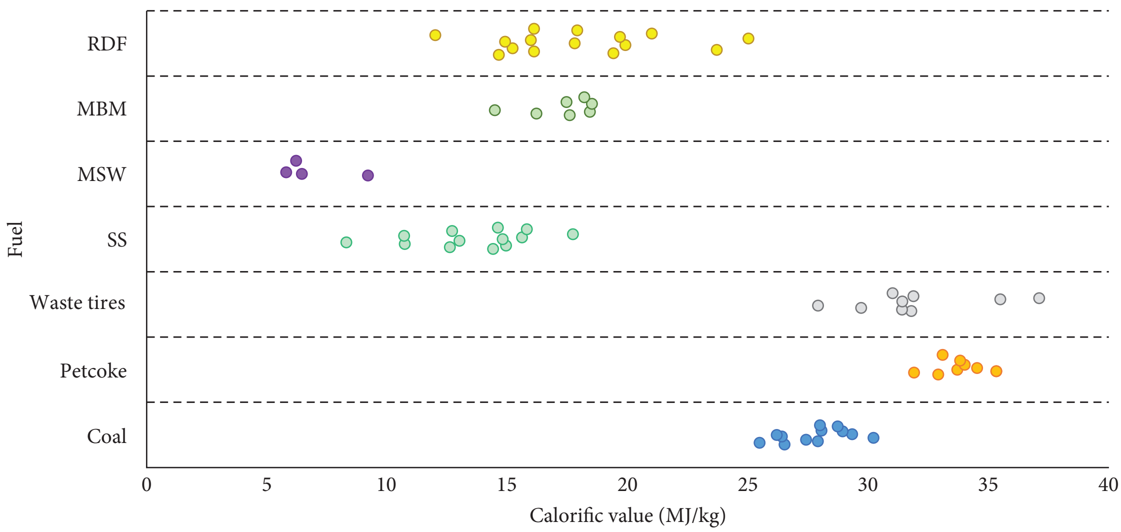

Figure 8: Calorific value of fuels in the cement industry [1, 9, 37, 51–56, 62, 72, 73, 77, 79–86, 88, 101, 103–108, 122–124, 129, 130].

AF delivery system, storage facilities for AF, and fuel distribution system [38]. On the other hand, the properties of AF are usually different from the traditional fuels. Therefore, in order to achieve uniform heating values, reconditioning operations (cleaning, drying, and homogenizing) must be conducted before the usage of AF, and preprocessing equipment must be installed [16].

4. Comparison of AF in Cement Industry

Figure 8 shows the calorific value of the conventional fuels (coal and petcoke) and AF that have been discussed in this work, namely waste tires, SS, MSW, RDF, and MBM. Generally, only the calorific values of the waste tires are comparable or higher than those of conventional fuels. On the other hand, the calorific value of MSW is the lowest, which may be attributed to its high organic content and moisture content. Nonetheless, the conversion of MSW into RDF significantly improves the calorific value.

According to Figure 8, it is observed that the calorific value of AF is relatively inconsistent compared to the calorific value of conventional fuels. This is attributed to the heterogeneous characteristics and properties of AF, even of the same type. Many factors can contribute to the inconsistency, including regions, the source of the wastes, composition of the wastes, technology to process the wastes, and more. Nonetheless, the standard deviation for the calorific value of the AF reported here is typically less than 3%, except for RDF. The standard deviation of the calorific value for coal, petcoke, waste tires, SS, and RDF is 1.44%, 1.03%, 2.79%, 2.54%, and 3.54%, respectively. MSW and MBM are excluded due to the limited data. The high standard deviation exhibited by RDF could be due to the source used to produce RDF, which is MSW. It is well known that the composition of MSW is different between places as it is highly dependent on various factors such as people's behavior, legislation, and more. Thus, these factors result in a RDF with unique composition and properties.

Based on this work, it can be said that waste tires may be the best option due to the following reasons:

(i) The calorific value of waste tires is high and comparable to conventional fuels. Its caloric value is within the class 1 classification according to BS EN ISO 21640.

(ii) The composition of tires is relatively consistent compared to MBM, MSW, RDF, and SS.

(iii) The wires in tires can be used as an iron source in clinker production.

(iv) The pretreatment of waste tires is simpler and less costly among others.

Although the high Zn content in waste tires could be problematic, however, the effect is negligible as long as the Zn content is below the threshold limits. Thus, a proper proportion while using waste tires in the fuel mix is required. Similar considerations shall be applied to any AF, especially those derived from waste. This is due to even of the same type, each AF is unique in nature.

On the other hand, the effect of the AF in the cement industry on the environment is found to be inconsistent, as detailed in Sections 3.1.1, 3.1.2, 3.1.3, and 3.1.4. This is due to the fact that the composition and properties of the AF may be different between regions. Furthermore, even in the same region, the technology, flue gas capturing system as well as fuel formulation between different plants may be different, which highly depends on the respective judgment and consideration. Thus, a comprehensive investigation on the feasibility of an AF to be employed needs to be comprehensively investigated before putting into application, based on the local context.

Therefore, it is inappropriate to conclude that one type of AF is superior to the others. Generally, the best AF option would be the one that aids in cost reduction, improves or maintains the current clinker quality, and does not cause additional or tremendous negative environmental impacts.

Nevertheless, it is practically impossible to have the best type of AF. The benefits of using AF in the cement industry while minimizing its negative impacts can be achieved through careful analysis and consideration. For instance, the MCDM method can be employed to facilitate the AF selection process [43, 44].

5. Conclusion

Although conventional carbon mitigation measures that are often proposed like energy efficiency improvements, use of AFs, and increasing materials substitution can only help to reduce the emissions associated with a small share of climate impacts [29], these are still regarded as a critical step in initiating and supporting the CO_2 reduction mission while emerging and innovative technologies such as CCUS may take time to be widely implemented. Moreover, the conventional mitigation measures are relatively simpler and can be put into action immediately without substantial changes to the industry itself.

There are various kinds of AFs available to be adopted in the cement industry, and four commonly used AF have been discussed, which are waste tires, MSW, SS, and MBM. Most of the investigations proved the feasibility of using AF in the cement manufacturing industry. Based on this work, the best AF option would be waste tires by considering its high calorific value and relatively easier handling process. Nevertheless, it is inappropriate to conclude that a type of AF is superior than the other as there are many factors to be considered besides the calorific value, including the availability, the local legislation, the technology, the price, the emissions, and more. Furthermore, even the same type of AF may have different combustion effects since they are not tailored for this purpose, and thus their constituents cannot be precisely controlled.

In a nutshell, the selection of AF always necessitates a thorough evaluation and careful consideration to avoid incurring additional costs, creating environmental issues, or degrading clinker quality. The MCDM approach is highly recommended to be used to analyze the suitability of an AF before putting it into the application.

Data Availability

The data supporting this work are from previously reported studies, which have been cited. The processed data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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