Comprehensive Evaluation of Waste-Derived Fuels As Sustainable Alternatives in Cement Production

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Abstract

The cement industry accounts for approximately 7–8% of global carbon dioxide (CO_2) emissions, primarily due to the energy-intensive clinker production process and reliance on fossil fuels. The environmental impact of this industry is particularly evident in the release of greenhouse gas (GHG) emissions. Therefore, the industry is exploring ways to reduce its energy costs and reliance on traditional fuels and mitigate environmental concerns by using waste-derived materials as a fuel substitute for cement production. In response to increasing environmental pressures, the substitution of fossil fuels with alternative fuels (AF) such as refuse-derived fuel (RDF), biomass, sewage sludge (SS), and used tires has emerged as a viable decarbonization strategy. This paper aims to provide a comprehensive analysis of AFs within the cement industry by reviewing previous studies, focusing on their GHG emissions and the technical, environmental, and economic implications of AFs adoption in cement kilns. A structured literature analysis was employed to evaluate fuel types, heating values, thermal substitution rates, combustion stability, and their effects on clinker quality. Data trends indicate that thermal substitution rates exceeding 80% are achievable with RDF and tire-derived fuels under optimized conditions, while biomass and SS require pretreatment for stable combustion. Environmental assessments report up to 30% reduction in CO_2 emissions and significant decreases in SOx and NOx with proper blending. The review also highlights key gaps in regional adoption and long-term performance evaluations. It concludes by recommending targeted policy support, plant-specific feasibility assessments, and integrated LCA-MCDM frameworks to scale the sustainable use of Afs.

Keywords: *Alternative fuels, cement industry, cement kiln, cement production, waste-derived fuels emission.*

1. Introduction

Cement production plays a key role in the global economy, as it, along with its main product, cement, is essential for major construction and infrastructure projects that support urban development. In light of the considerable energy demand for either thermal energy or electrical energy in cement production and the finite nature of non-renewable fossil fuels in its processes [1], [2], [3], this has raised significant environmental concerns. Also, using out-of-date production technologies further increases carbon dioxide (CO_2) emissions, making the cement industry the third-largest global CO_2 emitter, followed by power plants and the production of iron and steel [4], [5]. Producing one ton of cement via the dry process consumes approximately 3.2–6.3 gigajoules (GJ) of thermal energy and 110 kWh of electrical energy, depending on raw materials and technology used [6], [7], [8], [9], [10], [11]. Typically, cement production uses about 1.7 tons of raw materials, with thermal energy accounting for over 90% of the consumption [12], [13]. According to recent estimations, global cement production is approximately 4.1 billion metric tons per year [11], [14], [15], [16], [17]. These figures vary slightly each year based on demand and regional production levels. Figure 1 shows the total cement production by country in 2023 [17]. China dominated global cement

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production with 2,100 million metric tons, followed by India (410 Mt) and Vietnam (110 Mt), as shown in Figure 1. The cement production process begins with extracting raw materials, primarily limestone, which are ground together with other materials such as clay, silicon, iron, and aluminum to form raw flour.

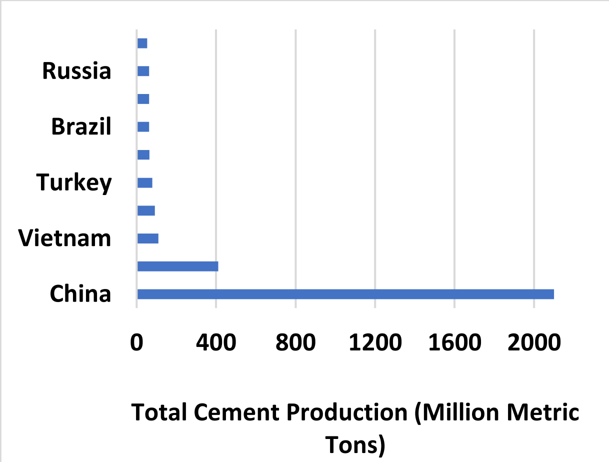

Figure 1. Country, total cement production in 2023 [17].

This mixture is fed into rotary kilns and heated to temperatures between 1200 and 1500°C, triggering calcination [18]. In these kilns, the mixture undergoes a partial melting process that leads to the formation of cement clinker. The formation of clinker occurs via calcination, during which calcium carbonate in the limestone decomposes, releasing calcium oxide (CaO) and CO_2 [19], generating 0.5 kg CO_2 per kg of clinker [6]. The resulting clinker is cooled, mixed with additives like gypsum & slag and finely ground into cement [20], [21]. The cement industry primarily relies on carbon-based fuels (fossil fuels) for thermal energy [22]. It contributes about 5–8% of global CO_2 emissions due to energy consumption [23], [24], [25], [26] and globally accounts for 27% of total direct CO_2 emissions, ranking as the second-largest emitter among industrial sectors [27].

Additionally, a ton of cement produced releases between 0.73 and 0.99 tons of CO_2 [28], depending largely on the clinker-to-cement ratio and other influencing factors. Other studies show that 1 ton of cement produces nearly 1 ton of CO_2 emissions [24], [29]. According to Madlool et al. [30], the cement manufacturing industry, being highly energy-intensive, uses roughly 60% to 65% of its total production on energy, with fuel costs accounting for 45% to 50% of that amount. In Figure 2, global cement production produced approximately 1.5 billion metric tons of CO_2 in 2023 [31].

With annual global cement production exceeding four billion metric tons, its environmental impact continues to grow, as shown in Figure 1, highlighting the urgent need for more sustainable manufacturing practices.

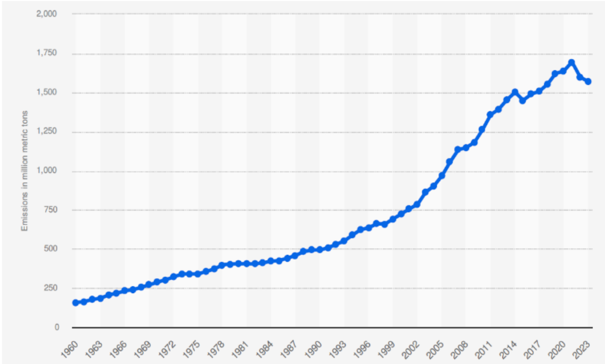

Figure 2. Global CO_2 emissions from cement production 1960-2023 [31].

Also, the types of fuel burned in the kiln (fossil fuels or alternative fuels) significantly affect the amount of CO_2 emitted during pyro-processing. Cement pyro-processing is the high-temperature stage in cement production where the materials undergo thermal decomposition and sintering at temperatures up to 1450°C to form cement clinker in a kiln [32], [33], [34]. This process highlights the substantial carbon emissions of the sector, emphasizing the need for more sustainable practices to reduce environmental impacts.

The cement production process is increasingly adopting renewable fuels to address heavy energy consumption within the sector, thereby reducing the cost of traditional fuel and environmental impact [35]. Alternative fuels from residues, including waste oil, plastics, refuse-derived fuel (RDF), solvents, tire-derived fuels (TDF), municipal solid waste (MSW), agricultural biomass, meat and bone meal (MBM), are promising for greenhouse gas (GHG) emissions reduction [30], [35], [36], [37], [38], [39]. These wastes can be solid or liquid, and are burned to generate energy used in cement production processes. Among these, RDF is a widely utilized waste material due to its high calorific value [35]. RDF is derived from processed solid waste and is also a recycled product that undergoes transformation processes before being utilized as fuel rather than direct waste combustion, offering a sustainable energy solution [40], [41]. Figure 3 shows different fuels used in cement clinker production, particularly within a rotary kiln. Alternative fuels can be categorized into biofuels, industrial waste-derived fuels, and municipal waste fuels [30], [36], [37],

[42], [43], [44]. Biofuels, such as agricultural biomass and SS, have shown promise due to their carbon neutrality [45].

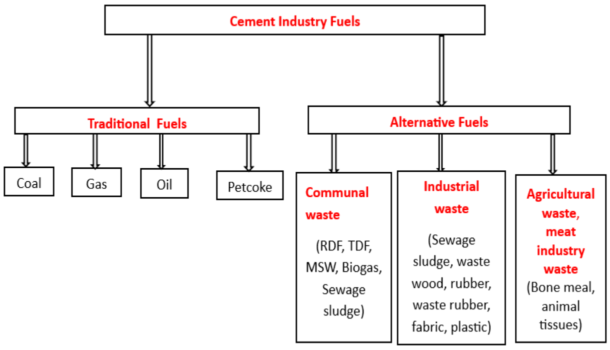

Figure 3. Traditional and alternative fuels used in the cement industry.

Industrial waste fuels, including used tires and solvent waste, have demonstrated high calorific values comparable to coal [46], [47]. However, MSW poses a challenge due to its heterogeneous nature and the need for preprocessing [48]. The use of waste fuels in cement production not only helps solve the issue of waste disposal but also leads to a reduction in the consumption of fossil fuels and the avoidance of additional emissions of pollutants [49].

This study aligns with several United Nations Sustainable Development Goals (SDGs), reinforcing its global relevance and impact. Specifically, it supports SDG 7 by promoting affordable and clean energy through fuel diversification in cement production; SDG 9 by encouraging industrial innovation via the integration of waste-derived fuels; SDG 12 by advancing responsible consumption and production through the circular use of waste materials; and SDG 13 by contributing to climate action through reduced greenhouse gas emissions in the cement industry [50].

1.1 Co-processing in the cement industry (benefits and challenges)

Co-processing is the practice of replacing fossil fuels in industrial processes, utilizing waste materials as raw materials, energy sources, or both, which has become a vital strategy for sustainable waste management and resource efficiency [51], [52]. This method supports economic principles by converting waste into valuable resources, reducing landfill use, and lowering GHG emissions [53]. Waste-derived materials can replace natural mineral resources or serve as recycled materials for energy recovery [20], [54], [55]. In cement production, co-processing in kilns offers a sustainable solution by recovering energy from various waste materials, improving production efficiency, and enhancing environmental sustainability [35]. For example, materials like MSW, agricultural residues, and industrial byproducts can replace traditional fuels like coal and oil in clinker production [53], [55].

Waste-derived materials in cement production offer significant benefits in both developed and developing nations with different driving factors. Replacing traditional fuels with combustible waste materials requires careful balancing of economic incentives, regulatory compliance, and environmental protection. This creates a commonly beneficial exchange between waste management and the cement industry, reducing reliance on non-renewable resources [56]. However, co-processing offers financial and environmental benefits while the operational challenges continue. Regulatory frameworks, particularly in developed nations like the USA and Europe, enforce strict pollution controls to reduce risks from toxic emissions in cement production [57]. While co-processing offers tangible benefits, its risks are particularly high in poorly regulated regions. It highlights the importance of regulatory oversight, technological advancements, and modified methods for different economic regions, as well as the ongoing evolution of waste management practices within the cement industry.

1.2 Introduction to waste-derived fuels in cement production

Waste materials such as industrial sludge, TDF, MSW, biomass waste, MBM, SS, etc, are commonly used as fuel substitutes in cement production [36], [39], [58], [59]. The use of waste-derived as alternative fuels in cement production has gained attention due to its environmental and economic benefits [60], [61]. These wastes help to reduce carbon emissions, lower energy use, reduce waste disposal and production costs, save natural resources, and reduce waste sent to landfill sites [61], [62], 63], [64], [65], [66]. However, only materials with high calorific value are suitable for use as alternative fuels, and processing steps such as moisture reduction, non-combustible material removal, and downsizing are essential to enhance their calorific value [21], [65].

Table 1. The element composition and combustion properties of various solid fuels.

Component (wt.%)	Agricultural Biomass		MSW	SS	RDF	TDF	MBM	Pet coke	Coal
	Rice Husk	Sugarcane bagasse							
Carbon	37.4	47.8	51.2	36.4–40.5	41.7–50.2	83.8–86.7	42.1–55.7	89.5–92.7	65.3–80.9
Chlorine				~0–1	0.7–1.13	~0	0.2	~0	~0–0.33
Hydrogen	5.4	5.9	6.2	4.7–7	4.4–7.8	6.9	5.8–8	2.4–3.7	3.7–5.1
Nitrogen	0.4	0.5	0.1	0.84–5.0	0.75–1.65	0.3–0.6	7.2–8.9	1.2–1.7	1.2–1.41
Oxygen	33.2	45.7	40.1	22	28.5–36.3	0.9–2.3	15.3–38.4	1.1–1.2	5.9–12.5
Sulfur				0.1–0.6	0.1–0.76	1.9–2	0.05–0.4	1.5–4	0.6–5.5
Moisture	9,2	9,2		5.2–5.6	3.7–20	0.9–1.9	1.4–8.1	0.8–1.5	1.1–3.3
Ash	18	2.9	4.4	17.9–29.5	10.2–13.8	3.3–4.4	10.4–28.3	0.5–1	6.4–15.5
Low Heating		14.9	17.2	8.0–15.8	13.7–17	27.4–31.7	16.9–28.8	28.9–35.4	21.9–31.8
High Heating	14.4	16.4		9.0–17.5	15.1–18.4	28.9–38.4	18.1–30.6	29.6–36.2	22.7–32.9

Among these waste-derived materials, RDF presents a high calorific value, thereby improving the environmental impact and production performance of cement production [39]. The production of RDF requires sorting, crushing, and shredding to reduce particle size, with size limits for cement kilns (<75–35 mm or <10 mm) and precalciner injection (≤100 mm) and its moisture, ash, and chlorine content should not exceed 25%, 20%, and 1%, respectively [40], [67], [68], [69]. Several studies confirm that RDF has combustion properties and elemental composition similar to traditional fossil fuels and has a higher calorific value than untreated MSW, making it a more energy-efficient and cost-effective solution to reduce the cost of energy, as summarized in Table 1 [25], [38], [39], [40], [68]. RDF also provides benefits such as more consistent composition, easier handling, lower emissions, and reduced air requirements during combustion [70].

The co-processing of MSW-based RDF in cement kilns is a scientifically proven and established technology that not only serves as an environmentally sustainable method for disposing of hazardous and non-recyclable waste but also demonstrates significant possibilities in replacing traditional fuel [69]. This paper presents a comprehensive assessment of alternative fuels in cement production, aiming to bridge critical gaps left by previous studies that focused on individual fuel sources or specific regions by reviewing wide studies on alternative fuels used in cement production to identify the best fuel blend for sustainable and efficient processes. Although past studies have explored alternative fuels like agricultural biomass, MSW, SS, and TDF etc, they lack integrated analysis of their impact on clinker quality, kiln efficiency, emissions, and economic viability. Also, most current studies focus on evaluating the impact of single alternative fuel types in cement production [71].

2. Classification of Alternative Fuels

Extensive research has been conducted on alternative fuels in the cement industry due to their potential to reduce GHG emissions and enhance sustainability. These alternative fuels are categorized into eight major groups: biofuels, natural gas, waste-derived fuels, wind energy, hydropower, solar energy, hydrogen, and nuclear energy [72]. In practice, alternative fuel options are mainly divided into three primary groups for use in cement production, as detailed by several researchers [20], [39], [44], [59], [65], [71], [72], [73], [74], as shown in Table 2 below.

Table 2. Groups of alternative fuel options for the cement industry.

Groups	Description
Gases	This includes refinery waste gas, natural gas, landfill gas and biogas, which offer a viable alternative to traditional fossil fuel-based energy sources.
Liquids	This includes used oils and solvents, which serve as a suitable alternative for powering cement kilns.
Solids	This includes used tires, paper waste, waste wood, plastic, rubber residues, animal meat, municipal waste, rice husks, domestic refuse and sludges, which can be converted into usable fuel, providing an alternative energy source to supplement or replace conventional fossil fuels.

2.1 Agricultural biomass

Agricultural biomass, such as wood chips or wood pellets, agricultural waste and organic waste, is considered a carbon-neutral fuel source and can be used as an alternative fuel in cement kilns because of its renewable nature and environmental benefits [75]. It has an approximate carbon footprint of zero, as the CO_2 crops absorb from processing biomass as fuel during combustion [72]. This balance makes agricultural biomass a more environmentally friendly option for fuel production than fossil fuels as we look for ways to combat climate change. Figure 4 illustrates types of agricultural biomass, such as bagasse, wheat straw, maize cob, rice straw, and cotton straw, used as alternative fuels in cement production.

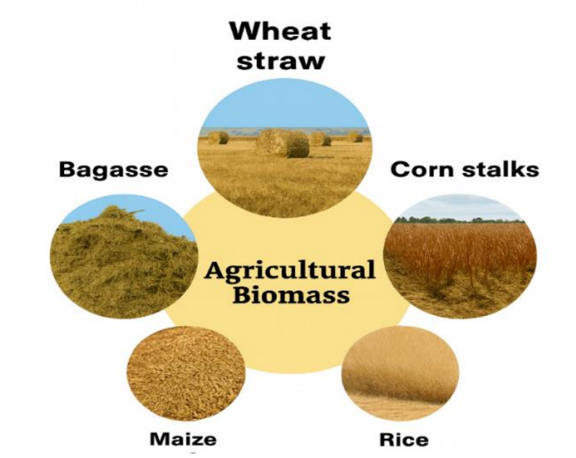

Figure 4. Agricultural biomass.

Table 3 presents the calorific values and the emission factors of agricultural biomass residues [76], [77], [78]. The latent heating values of these materials were obtained from the literature. Previous studies have assumed that 25% of crop residues are burned in the field. To achieve a 20% substitution of coal with bagasse, we need 61.09 kg of coal and 17.71 kg of bagasse to fulfill the thermal energy demand to produce one ton of clinker. A similar approach applies to other material mixtures [77].

Table 3. Calorific and emission factor values.

Material	Calorific values (MJ/kg)	Emission factors (kg/kg)	
		CO_2	CO
Bagasse	19.8	1.13	0.0347
Wheat straw	19.5	1.55	0.1412
Maize cob	18.6	1.26	0.1147
Rice straw	17.1	1.10	0.0532
Cotton straw	20	1.34	0.10582

Co-processing of agricultural biomass residues has been identified as an effective method for NOx emissions reduction in cement kilns. When ammonia (NH_3) combines with NOx, it forms nitrogen gas (N_2), a harmless and naturally occurring gas [72]. However, the sulfur content in agricultural biomass varies significantly, thereby leading to inconsistency of SO_2 emissions during co-processing. This variability poses a challenge for cement producers seeking to optimize fuel blends for emissions reduction. Although the environmental advantages of agricultural biomass are recorded extensively, there is limited research on the long-term impact of biomass co-processing on clinker quality and kiln performance.

2.2 Municipal solid waste (MSW)

MSW is a municipal waste product that can be processed into alternative fuels, such as refuse-derived fuel (RDF), for cement kiln operations, providing energy recovery and reducing landfill usage [74]. Despite this, the cement industry faces challenges in reducing CO_2 emissions, primarily due to calcination, a process largely unaffected by fuel changes or efficiency improvements. MSW generation worldwide averages 440 kg per person annually, contributing to environmental and health risks due to hazardous pollutants [79], [80]. Managing this waste is becoming more difficult due to population growth and limited landfill sites. The incineration reduces waste volume by 70-90%, but it presents operational challenges like incomplete combustion and increased energy use, which have led to the exploration of gasification technologies [71], [79], [81], [82], [83].

Although gasification is proposed as a possible solution, its application in cement production remains limited [75]. The MSW composition varies across different regions significantly due to cultural and waste management practices, which can make it difficult for cement plants to use unsorted MSW as a fuel source, as it may contain materials unsuitable for burning [66]. As a result, most cement industries do not burn unsorted MSW directly due to its heterogeneous nature, which can cause combustion issues [59]. The typical composition of MSW by material type is detailed in Table 4 [65], [66].

Table 4. Composition of MSW by weight percentage.

Component	Ash	C	Cl	H	Moisture	N	O_2	S	VM	Heating value (MJ/kg)
MSW dry solids (%)	35.17	34.88	1.02	4.65	31.2	1.02	23.11	0.15	64.8	15.4
RDF dry solids (%)	10.9	47.1	0.6	7.1	15	0.7	29.4	0.24	82.06	21.2

Untreated MSW often has low calorific value content (6.21 to 13.9 MJ/kg) and high moisture levels, making it inefficient to burn. It may also include non-combustible materials that further lower its calorific value. [84, 85]. More studies are needed on the gasification of MSW in cement kilns, particularly its impact on emissions, clinker quality, and kiln efficiency. Additionally, the economic feasibility of MSW gasification compared to traditional combustion methods requires further investigation.

2.3 Sewage sludge (SS)

The wastewater treatment process produces large amounts of SS waste, posing significant waste management challenges, particularly for wastewater treatment facilities. [65], [72]. SS waste originates from industrial, domestic and cleansing water sources. The current sludge applications are utilized mainly in ways damaging to the environment, with common uses including landfilling and employment in agriculture as an organic fertilizer and soil additive [72]. Figure 5 shows the SS sample.

Figure 5. Sewage sludge [86].

Sludge waste is high levels of organic material, minerals, and water. It can decompose and contain hazardous substances like heavy metals, PAHs, PCBs, and dioxin [87], which are harmful to humans and damage the environment. The calorific value of sludge ranges from 8-17 MJ/kg [72]. It is influenced mainly by the initial processes that resulted in the production of the wastewater and the subsequent methodologies applied for sludge treatment. The main components of SS waste include aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), iron oxide (Fe_2O_3), and calcium oxide (CaO), which are vital in cement clinker production. The mineralogical characteristics of SS were examined through X-ray diffraction (XRD) analysis [88], as illustrated in Table 5 [88]. Using dried SS as a fuel substitute in cement kilns provides calorific energy without generating additional emissions [89]. Co-processing SS in cement kilns significantly reduces CO_2 equivalents per ton of dried sludge compared to other methods [90]. A key characteristic of SS is its high water content, which is crucial in gasification and combustion processes [91].

Table 5. The chemical composition of sewage sludge for cement production.

Chemical composition	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	P_2O	SiO_2
Content (wt%)	5.63	6.35	4.15	1.18	1.54	4.85	25.19

The drying process is necessary for the production of SS to reduce the water content of the sludge using waste heat from cement kilns, where SS is either burned directly in the kiln or gasified for use in kilns, heaters, or pre-calciners [89]. Adopting dried SS as a fuel or raw material substitute in cement production has been explored and confirmed to be feasible, primarily due to its calorific value and the high temperatures in cement kilns, which can effectively destroy hazardous substances found in SS, making it a suitable method for sludge management [88]. Several studies have indicated that using SS as an alternative fuel does not negatively impact the quality of clinker [66], [88], [92], [93], [94]. However, some substances in SS may transfer into the clinker as its ashes integrate during the calcination process, requiring careful consideration.

Yang and Zhang [88] proposed utilizing SS as both fuel and raw material in cement clinker production, emphasizing that excessive sludge can negatively affect tricalcium silicate formation. Their study also highlighted the significant presence of trace elements such as zinc and manganese in SS during calcination, which can influence cement quality. Fang, et al. [94]

researched using SS as an alternative fuel in a Chinese cement plant to reduce NO_X emissions. They identified the sludge feed rate, feed point, and feed method as critical factors in achieving emissions reduction while maintaining clinker quality. Haibing, et al. [92] investigated SS waste as a fuel substitute and found no adverse effects on cement production. However, they observed an increase in setting times that remained within acceptable limits. Rećko [86] focused on producing alternative fuels from SS, plastic, and wood waste, with calorific values ranging from 16.5 to 33 MJ/kg, confirming their potential for cement production. Husillos Rodríguez, Martínez-Ramírez, Blanco-Varela, Donatello, Guillem, Puig, Fos, Larrotcha and Flores [95] demonstrated that thermally dried SS could reduce fossil fuel consumption by 70% and replace up to 14% of raw materials in cement production without compromising raw meal quality.

2.4 Refuse-derived fuel (RDF)

RDF is produced by shredding and drying MSW and separating it into combustible and non-combustible fractions. It serves as a substitute for fossil fuels in cement kilns and is widely used in many European countries [61], [96]. The production of RDF is achieved by removing non-combustible materials from various waste streams and its use poses environmental challenges, such as exposure risks during handling and transportation due to its low density and energy content [65]. Figure 6 illustrates an RDF landfill site.

Figure 6. A refuse-derived landfill site [97].

RDF is preferred as an alternative fuel source in cement production over MSW due to its higher heating value, lower moisture content, and greater efficiency, thereby making it a more environmentally friendly fuel source [65]. Directly burning MSW in cement kilns is not feasible due to its heterogeneous nature and chemical composition, which can affect burning quality [48]. Countries like Jordan, Italy, Belgium, Denmark, and the Netherlands have adopted RDF in cement kilns [61], [98]. However, RDFs exhibit varied physical and chemical properties, such as ash, chlorine, sulfur, and moisture content, based on their sources, causing challenges for direct combustion in kilns. The use of RDF as a secondary fuel in cement production is a cost-effective solution that also reduces the demand for landfill space.

2.5 Tire-derived fuels (TDF)

Waste tires are a byproduct generated by the automobile industry. They have become increasingly common due to the widespread use of vehicles as a primary mode of transportation. Around 3 billion tires are discarded worldwide each year, with significant contributions from the United States, Japan, and the European Union, which together generate nearly 5 million tons of waste tires annually [99], [100]. Approximately 70% of these tires are recycled, often used as fuel in cement kilns or as raw materials in new products [101]. Cement kilns are perfect for this application due to their high calcination temperatures and stable combustion conditions. Using waste tires in this way reduces dependence on fossil fuels and saves natural resources, thereby supporting sustainability [20], [102].

However, innovative strategies are still required to manage the increasing volume of waste tires effectively. Figure 7 (a-c) illustrates the types of waste tires used as alternative fuel. Since the 1980s, the cement industry has increasingly adopted waste tires as fuel in kilns due to rising fossil fuel prices and the tires' high energy content [96]. TDF has a net calorific value ranging from 27–37 MJ/kg, comparable to coal and petroleum coke, and burns quickly, making it an efficient alternative fuel for co-processing in cement production [60], [74], [102], [103], [104], [105], [106], [107].

Cement kilns operating above 1,450°C ensure the complete combustion of tires, minimizing harmful emissions while maximizing energy recovery [102]. Waste tires, composed mainly of carbon (76–88 wt%) and oxygen, decompose above 1,000°C, releasing gases that enhance combustion [108].

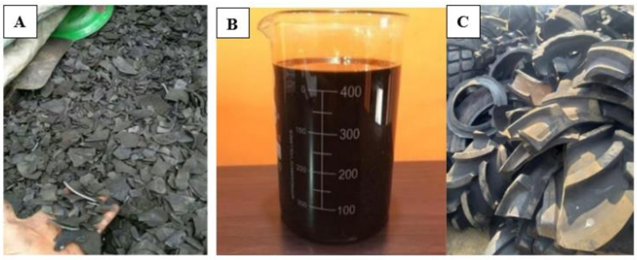

Figure 7. (a) Waste tires, (b) Tire chips and (c) Tire-derived fuel [96].

Using TDF provides both economic and environmental benefits, i.e., it supports sustainability by reducing fossil fuel use, cutting costs, and diverting tire waste from landfills or incineration. The utilization of TDF as a fuel substitute in cement production reduces waste to landfill sites, generating revenue streams and mitigating environmental impacts, health, and safety risks [96], [107], [109]. It also has a low moisture content (<2%), is cost-effective, and contains valuable metals such as zinc and iron [110]. Table 6 shows the comparative analysis of TDF and coal.

Table 6. Comparative analysis: TDF vs. Coal.

Parameter	TDF	Coal
Calorific Value	27–37 MJ/kg	25–35 MJ/kg
CO_2 Emissions	15–20% lower	Baseline
Cost	€75–100/ton (25% lower)	€100–130/ton
Heavy Metals	Lower (except Zn)	Higher

Data source: [60], [74], [102], [103], [104], [105], [107], [111].

Castañón, et al. [60] investigated the opportunity of using a waste tire as a fuel substitute in cement production, evaluating its impact on emissions, clinker quality, and economic costs. They analyzed and compared emissions when substituting pet coke with TDF (40%) and their economic assessment revealed a significant reduction in annual fuel costs, estimating annual fuel expenditures for pure petroleum coke amount to about €8,000,000, whereas using TDF reduces costs to €5,938,000, i.e., TDF is 25% cheaper than petroleum coke, making it a good alternative fuel for cement production.

Fiksel, Bakshi, Baral, Guerra and DeQuervain [112] reported that substituting coal with TDF in cement kilns prevents approximately 543 kg of CO_2-equivalent emissions per ton of clinker while maintaining clinker quality, offering economic and environmental benefits. However, Prisciandaro, Mazziotti and Vegliò [113] observed an increase in SO_2 and NO_x emissions at a 20% TDF substitution rate during co-processing in an Italian cement plant, with emission levels varying due to site-specific process configurations and combustion parameters. Comparative emission analyses have demonstrated that the burning of TDF in cement kilns exhibits superior environmental performance relative to coal burning, with significantly reduced emissions of dust, anthropogenic CO_2, NO_x, and most heavy metals (excluding zinc) under standardized operational conditions [111]. Despite these problems, TDF is a promising solution for mitigating the environmental impact of waste tires, offering benefits such as high heating value and affordability while addressing the global tire waste problem.

2.6 Meat and Bone Meal (MBM)

MBM is a byproduct processed via rendering of crushing and cooking animal offal and bones from slaughterhouse waste [114]. It serves as a potential alternative fuel in cement production [72]. However, its lower heating value compared to fuels like TDF or RDF requires burning larger quantities to match energy output, increasing CO_2 emissions [115]. MBM has a nitrogen content of approximately 7-8 times higher than coal, producing higher NOx emissions. However, blending MBM with coal mitigates this. Its high calcium content reduces SO_2 emissions by reacting with sulfur, yet excess calcium can form free lime, compromising cement quality [65], [72]. SO_2 levels during co-processing depend on sulfur content and CaO in ash, which acts as a natural desulfurizer [72]. Although MBM offers partial environmental benefits, but challenges like higher CO_2, NO_x risks, and quality concerns limit its viability as a sustainable fuel. Safe disposal of MBM waste is critical due to prohibition of using MBM residue in animal feed or disposing of it in landfills sites [59]. Co-processing MBM in cement plants offers energy recovery and aligns with waste management goals [116]. The close analysis of MBM and coal shows that MBM contains higher moisture (6.8% vs. 4.2%) and ash (34.4% vs. 6.2%), lower fixed carbon (26.1% vs. 53.0%), and comparable volatile matter (32.7% vs. 36.6%) [117].

After burning, MBM produced only 20-30% of its original weight as ash. This significant reduction in volume shows how much material is eliminated during combustion [118]. Also, it highlights its potential for sustainable disposal while addressing logistical and environmental challenges in waste management systems. Existing studies on MBM as a cement industry fuel focus on emissions (CO_2, NO_x, SO_2) and waste management benefits [115], [116], [118], [119] but lack integrated analysis of trade-offs. The impact of MBM co-processing on clinker quality and kiln performance remains underexplored. Additionally, there is a need for more research on the optimal blending ratios of MBM with other alternative fuels to minimize emissions and maximize energy efficiency.

2.7 Solvent and waste oil

Waste oil, a hazardous byproduct that originates from automobiles, agriculture, industry, and transport, is used as a fuel substitute in cement production [66] due to its high calorific value (29-36 MJ/kg) and minimal processing costs, dependent on chemical composition [47], [65]. However, co-processing solvents and waste oils in cement kilns fail to reduce CO_2 emissions effectively [47]. Emissions saved from avoiding conventional energy production are offset by those generated during co-processing, resulting in a net environmental burden. Calorific value varies with the chemical composition of the waste oil and solvent components in Table 7 [65], affecting fuel efficiency [65]. Despite their energy potential, the environmental impact of waste oils remains significant due to unresolved emissions.

Table 7. Chemical compositions of waste oil and solvent by weight percentage.

Composition	H	C	S	H_2O	O	N	Cl
Waste oil (%wt.)		84	0.83		14.73	0.44	20
Solvent (%wt.)	8.2	47.7	0.7	16.5	23.1	1	2.4

Spent solvents and waste oils can be used as alternative fuels in cement kilns without requiring pre-treatment, as they are compatible with existing oil firing systems designed for paraffin or kerosene, which initiate combustion in the burner [47], [65]. These liquid wastes can be injected directly into the burner or calciner. However, co-processing lubricants may increase CO_2 emissions due to their lower thermal efficiency Kaddatz, Rasul and Rahman [120]. Solvents can raise NOx emissions by up to 20%, whereas waste oils may help reduce NOx emissions depending on combustion conditions [121], [122]. Cement plants near industrial zones benefit from spent oil and solvents as a readily available fuel source, thereby reducing transport costs [47]. Nonetheless, the effect of chemical variability on emissions, efficiency, and treatment requirements is still poorly understood and needs further investigation.

3. Benefits 0f Alternative Fuel in The Cement Industry

3.1 Environmental benefits of switching to alternative fuels

Cement production contributes about 8% of global CO_2 emissions, but using waste-derived fuels can cut this by 15–30% [123]. Alternative waste-derived materials like TDF, plastics, and biomass present significant environmental and operational benefits [49], reduce fossil fuel use and prevent resource depletion [20]. They also lower air pollution from open burning and safely neutralize hazardous waste in kilns, offering both environmental and operational advantages. Pitak, Rinkevičius, Kalpokaitė-Dičkuvienė, Baltušnikas and Denafas [124] developed a process to produce solid recovery fuel (SRF) from RDF and assessed its use in Lithuania's cement sector. Replacing 10% of coal with SRF reduced CO_2 emissions by 3.7 t/h and saved 601.7 USD/h in coal costs, with a net saving of 754.7 USD/h. SRF also helps cut waste disposal by up to 50%. By diverting organic waste from landfills, it prevents methane emissions, which have 250% more global warming potential than CO_2 [125], [126]. Reza et al. (2013) showed through LCA that replacing coal with alternative fuels in cement kilns reduces GHG emissions, smog, acidification, eutrophication, carcinogenic risks, and landfill costs. Efficient combustion at 1,450°C enables energy recovery and lowers emissions. Waste-derived fuels, often containing biogenic carbon, integrate into the carbon cycle [127]. Diverting MSW from landfills further reduces environmental risks, improving sustainability in cement production [128].

3.2 Technological benefits of switching to alternative fuels

The high-temperature treatment effectively eliminates organic materials present in the residues. The process involves exposure to temperatures of 2,000°C and a controlled atmosphere with a short residence time (4-5 seconds). This method ensures thorough sterilization and organic matter removal. Cement production involves burning, which generates acidic gases. These gases are neutralized by the alkaline raw materials used in cement production, leading to the formation of stable compounds. These compounds are incorporated into the clinker, a key component of cement. According to theoretical modeling and empirical data, a modern cement kiln with six cyclone stages requires an average of 3,000 to 3,400 megajoules (MJ) of fuel energy per ton of clinker produced. To further refine optimal substitution rates, future experimental studies should adopt orthogonal design approaches similar to those applied in [129], which systematically evaluated mechanical performance by varying component proportions in high-performance concrete.

In contrast, a kiln with five cyclone stages requires an average of 3,100 to 3,500 MJ of fuel energy per ton of clinker produced. The interaction between the kiln's flue gases and the raw materials effectively reduces the non-combustible residues. Burning waste in cement kilns instead of incinerators results in lower overall CO_2 emissions, as cement kilns more efficiently capture and use CO_2 during combustion, reducing CO_2 penalties. From a life cycle perspective, using low-grade alternative fuels in precalciners is environmentally preferable to incineration, as it lowers NOx emissions and supports efficient combustion at lower temperatures. Precalciners also enable reburn reactions that convert NOx into harmless gases, improving the sustainability of cement production.

To enhance the scientific robustness and comparability of future experimental studies on alternative fuels in cement production, it is essential to incorporate standardized high-temperature testing protocols. This includes the use of controlled thermal exposure regimes and post-exposure performance evaluations to assess the mechanical and microstructural behavior of clinker influenced by fuel-derived residues. Specifically, methods as detailed in Luo, Jia, Wang and Cheng [130], which involve systematic heating profiles and evaluations of residual strength and microstructure, should be considered as a best-practice framework when investigating high-temperature behavior. Such methodology will help establish reproducible data for optimizing substitution ratios and understanding phase transformations under thermal stress.

3.3 Economic benefits of switching to alternative fuels

The adoption of alternative fuels in the cement industry offers significant economic benefits, primarily through cost reduction and enhanced sustainability compliance. Chatziaras, Psomopoulos and Themelis [131] emphasized the economic benefits of alternative fuels such as RDF, TDF, SS, MSW, and waste-derived fuels. Substituting traditional fossil fuels with lower-cost alternatives, such as waste-derived fuels, can reduce fuel expenses by 10% [132], [133]. Additionally, alternative fuels mitigate carbon tax liabilities and compliance costs under emissions trading systems. Cement producers using waste fuels report 15-20% lower CO_2 emissions [134], reducing exposure to carbon pricing mechanisms. For instance, India’s cement sector saved energy and production costs through co-processing incentives [135]. Alternative fuels are often obtained at lower or even zero cost compared to traditional fossil fuels. The energy contribution and economic benefits of utilizing plastic waste as a fuel substitute in the cement industry yield a 241% annual increase in plastic waste usage, saving 1.99 billion/year and reducing marine pollution [136]. Operational efficiency also improves through waste-derived fuel partnerships.

Reza, et al. [63] found that producing and using RDF in cement production is both environmentally and financially viable, offering economic benefits to municipalities, customers, and society in Canada. Economically, the substitution of fossil fuels with waste lowers operational costs. It generates revenue through waste processing fees, incentivizing industry adoption. Cement plants can secure long-term, low-cost fuel contracts with municipalities or industries seeking waste disposal solutions, ensuring price stability amid fossil fuel volatility. This approach contributes and promotes a more sustainable waste management solution and a greener cement production process.

4. Disadvantages of Alternative Fuel in the Cement Industry

Despite the advantages of alternative fuel, there are still some challenges that need to be addressed in the development of the alternative fuel market. Changing from traditional fossil fuels to alternative fuels for thermal energy supply in cement kilns offers significant advantages, either entirely or partially. However, there are several challenges to consider due to the varying properties even within the same type compared to fossil fuels. These differences require careful handling and adjustments. The cement industry faces several problems when using alternative fuel, such as poor heating distribution, unpredictable precalciner performance, blockages in the preheater cyclones and accumulation in the kiln riser ducts. These issues require meticulous management and may need process modifications to ensure optimal performance and efficiency.

Some research shows that alternative fuels can result in higher emissions of certain gases, including SO_2, NO_x and CO [137]. This increase is attributed to the specific composition of the alternative fuels being used in the process. Alternative fuels with greater sulfur and nitrogen concentrations require special attention. The ratio of alternative fuel to conventional fuel and the filtration system of the cement kiln can contribute to these issues. Consequently, thorough investigations and continuous monitoring are essential when implementing alternative fuels in cement production, given the complexity of such transitions. Another significant concern of using alternative fuel in the cement industry is the potential of incorporating ash residues into the clinker, which can affect clinker quality and the cement, the final product. These ashes differ from those generated by traditional fuels and may introduce unwanted elements into the cement kiln [71]. Therefore, effective control and management are essential to maintain clinker quality and ensure the safe and sustainable use of alternative fuels.

5. Comparison of the Implementation of Alternative Fuels

The comparisons of the calorific value show a broad energy potential among traditional and alternative fuels in cement production. While many cement plants prefer alternative fuels with a calorific value above 14 MJ/kg for stable operation, lower-value fuels can also be utilized effectively, particularly in precalciner zones or at lower substitution rates, provided appropriate process adjustments are made [72].

Based on the review, used tires and certain types of biomass can offer cost-effective and high substitution potential under favorable local conditions, making them among the most promising alternatives to traditional fuels, depending on site-specific factors such as availability, infrastructure, and regulatory context. Waste oil, MBM, and TDF have calorific values comparable to or higher than coal (25–27.5 MJ/kg), requiring minimal processing [72]. TDF has proven to be the best option and promising alternative fuel in the cement industry for many years [138], with energy content ranging from 23–35.6 MJ/kg [60], [102], [114], [139], [140], [141], while petcoke with calorific values from 22.1–39.5 MJ/kg provides high energy but may increase CO_2 and SOx emissions [61], [114].

RDF, derived primarily from MSW, exhibits lower and more variable calorific values between 11.72 and 20.0 MJ/kg, requiring preprocessing to improve consistency and combustion performance [98], [142], [143], [144]. Biomass, including agricultural residues, provides 13.4 to 18.0 MJ/kg, offering renewable carbon-neutral energy potential [59], [72]. Nevertheless, the limited availability of a specific type of agricultural biomass throughout the year hinders its widespread use. At the lower end of the calorific value range, SS and MSW range between 0.8–8.37 MJ/kg and 5.8–13.9 MJ/kg, respectively, reflecting high moisture and inert content that necessitates that SS must be dried and MSW must be shredded, then pelletized for co-processing [84], [85], [95]. The SS produces less energy during combustion due to its low calorific. However, the ash produced during combustion can be used as an alternative raw material in specific industrial processes, offsetting the lower energy content. MBM provides a moderate-to-high energy range (14.0–28.0 MJ/kg) with notable variability, dependent on feedstock and processing methods [119], [145]. MBM must be dried and ground before using in a cement kiln. The high moisture content of both MBM and MSW hinders their large-scale utilization.

Waste oil, typically industrial or automotive in origin, offers a favorable range of 14.65–34.0 MJ/kg, approaching the energy density of fossil fuels. However, its chemical variability may require controlled feeding systems [61], [72]. The calorific value of alternative fuels exhibits a notable variability compared to traditional fuels due to their heterogeneous properties, even within the same category. The inconsistency in the calorific value of alternative fuel can be attributed to a range of factors, including differences in geographical location, waste sources, waste composition and the available technology for handling it, etc. Despite various studies aimed at identifying the potential advantages and obstacles of utilizing different alternative fuels, the best choice remains undecided because selecting the best fuel depends on numerous criteria considered from various perspectives. These criteria are not limited to cost, environmental impact, availability, and infrastructure.

Table 8 presents the percentage of the different waste-derived fuels used in the cement production process [49], [66], [146]. Alternative fuels are categorized as non-traditional materials (e.g., waste, biomass, tires) instead of conventional fossil fuels like coal, pet coke, or gas. Between 2011 and 2021, major cement producers exhibited varying shifts in fuel usage. In 2011, Holcim Group plants achieved very high alternative fuel substitution rates, particularly through the use of industrial waste and other non-traditional fuels. By 2021, it reduced its alternative fuel mix to approximately 21%, indicating a significant decline in alternative fuel usage, maintaining fossil fuel dominance. Cemex Group reported high levels of alternative fuel usage in several plants, including tires, industrial and household waste, MBM, and biomass. However, by 2021, the group's reliance on fossil fuels increased to 70.8%, with fossil-based waste and biomass-based alternatives declining to 10.7%, indicating a significant reduction in substitution levels. Between 2011 and 2020, certain Heidelberg Cement plants achieved high alternative fuel substitution rates, often exceeding 80% with a shift in fuel mix from plastics, wood chips, and agricultural waste to increased use of RDF and other biomass sources.

Meanwhile, Titan Alexandria Portland Cement Company, which used nearly 100% fossil fuels (natural gas, diesel) in 2014, shifted by 2020 to 81.6% coal and 12.2% RDF, reflecting a partial but notable shift toward alternative fuel sources [147]. Titan Cement significantly increased its use of alternative fuels from 0% in 2014 to 17.1% in 2020. This shift in fuel types allows for the assessment of emission changes compared to 2014. These trends reflect divergent strategies in balancing fossil fuels and sustainable alternatives across the industry. These trends highlight different tracks in the cement industry's fuel adoption over the past decade. Holcim Group and Cemex Group showed a decline in the percentage of alternative fuel usage by 2021. Heidelberg Cement maintained 100% alternative fuel usage, with changes in fuel types, while Titan Alexandria had the lowest adoption rate (21%) among the listed companies. There is no single best alternative fuel for the cement industry, as the best choice depends on factors like availability, cost reduction, and impact on clinker quality and the environment. The benefits of using alternative fuels include lower GHG emissions and resource conservation. The cement industry can use the Multi-Criteria Decision-Making (MCDM) method to optimize alternative fuel selection, which evaluates various alternative fuel options based on predefined criteria.

Table 8. The percentage of the different waste-derived fuels used in the cement industry.

Holcim Group (2011)	(%)	**Holcim Group (2021)**	(%)
Waste oil	5	Coal	32
Solvent and liquid waste	11	Pet coke	24
Tires	10	Oil	3
Impregnated sawdust	7	Gas	19
Plastic	9	Other traditional fossil fuels	1
Industrial waste and other fossil-based Fuel	30	Other alternative fuels	13
MBM	2	biomass	8
Agricultural waste	9		
Wood chip and other biomass	15		
Sewage sludge	2		
Total	100		100
Cemex group (2011)		**Cemex group (2021)**	
Tires	16	Petroleum coke	44.7
Industrial and household waste (solid)	65	Coal	18.5
MBM	4	Fuel oil + Diesel	1.1
Agricultural waste	10	Natural gas	6.5
Wood chip and other biomass	5	Fossil-based waste	18.5
		Biomass waste	10.7
Total	100		100
Heidelberg Cement (2011)		**Heidelberg Cement (2020)**	
Waste oil	3.7	Refuse Derived Fuel (RDF)	27.5
Solvent and liquid waste	4.7	Waste oil	3
Tires	11.6	Used tyres	9.5
Plastic	26.4	Solvents	7
MBM	6.1	Dried sewage sludge	1.8
Agricultural waste	4.2	Meat and bone meal	3.3
Wood chip and other biomass	24.5	Agricultural waste and waste wood	7.7
Sewage sludge	4.2	Other biomass	25.8
Other alternative Fuel	14.6	Other alternative fuels	14.4
Total	100		100
Titan Alexandria Company (2014)		**Titan Alexandria Company (2020)**	
Natural gas	97.3		
Diesel	2.7	Diesel	1.3
		Coal	81.6
		RDF	12.2
		Dried SS	0.1
		TDF	4.8
Total	100		100

6. Conclusion

This paper presents a detailed analysis of alternative fuels from waste for cement production, highlighting their potential for GHG emissions reduction, energy costs reduction and lowering operational costs through a critical evaluation of alternative fuels, such as RDF, TDF, MSW, SS, MBM, agricultural biomass, solvents and waste oils. It highlights the opportunities and complexities related to traditional fossil fuels in the cement industry. The fuels have been carefully evaluated based on their calorific values, emissions and environmental impact. The results confirm that TDF and RDF offer considerable benefits due to their high calorific values, cost-efficiency and combustion performance. TDF, in particular, demonstrates strong economic possibility due to a higher calorific value than other alternative fuels, with estimated savings of millions of dollars annually per facility, and has proven effective in maintaining cement quality. Specifically, substituting 20% of coal powder with TDF has been shown to reduce fuel costs by approximately 18–22%, while reducing CO_2 emissions by 15–17%, depending on plant configuration, fuel blending ratio, combustion efficiency and local fuel market conditions. However, the lack of research regarding the maximum safe substitution rates for alternative fuels like TDF and underexplored fuels like waste oil remains a critical research gap. MSW also emerged as a possible alternative material due to its availability and capacity to offset reliance on fossil fuels. However, its high moisture content and heterogeneous composition present handling, storing and processing challenges. Also, the high moisture content in MBM presents difficulties in processing, thereby making it harder to manage efficiently and affordably. These fuels must not be evaluated only for their energy potential but also for their impacts on clinker quality, refractory integrity,

The paper emphasizes that fuel selection must be context-specific, taking into account geographical variability, waste characteristics, technological maturity, and regulatory environments. While the challenges associated with using waste as a fuel source exist, advances in technology and infrastructure are making it an increasingly possible option for cement producers. As the industry continues to seek sustainable solutions, using waste as a fuel substitute is likely to play a growing role in the future of cement production. This necessitates strict monitoring and control systems to mitigate environmental risks. Strategic investment in infrastructure, particularly in developing regions, as well as supportive policy frameworks and public-private collaboration, will be pivotal in scaling up adoption. Integration with carbon capture, utilization, and storage technologies, alongside broader industrial symbiosis, will further improve sustainability outcomes.

In conclusion, while challenges remain, alternative fuels present a possible pathway for cement decarbonization. Also, these fuels offer numerous benefits from both environmental and economic viewpoints, including reduced waste disposal costs, lower production and energy costs, and reduction of GHG emissions, thereby giving cement industries that adopt this energy source a competitive advantage in the market. Emissions of NO_x, SO_2, and heavy metals demand close attention, effective control and strong management to reduce environmental impact. Future research should focus on optimizing blending strategies, refining preprocessing techniques, and improving emissions management to maximize the adoption and performance of alternative fuels. Moreover, integration of the Life Cycle Assessment and Multi-Criteria Decision Making (LCA–MCDM) framework is recommended to facilitate informed, balanced fuel selection of alternative fuels based on environmental, technical, and economic criteria.

Although this review does not present original experimental data, future studies should aim to investigate the microstructural influence of alternative fuel combustion residues on clinker mineralogy using advanced techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS). Insights from recent research on nano-silica and fiber-reinforced recycled concrete [148], [149] demonstrate how microstructural modifications can significantly affect phase formation and mechanical performance. Applying similar methodologies to analyze cement clinker modified by RDF, TDF, or SS residues would help clarify the transformation behavior of mineral phases such as C_3S and C_2S and establish more robust fuel–process–product correlations.

Conflicts of Interest

The authors declared no potential conflicts of interest concerning the research, authorship and publication of this article.

Data Availability Statement

Supplementary materials and data used in this research are accessible upon request. For access, please contact the corresponding author via oluwafemiI@dut.ac.za or phemmyigoh@yahoo.com

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