Opportunities and challenges of using SRF as an alternative fuel in the cement industry

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A B S T R A C T

Over two billion tonnes of municipal solid wastes (MSW) are generated annually from households, industrial facilities, and commercial sites. The non-hazardous fraction of MSW is used to produce solid recovered fuels (SRF), which have an economic and environmental value when used as a substitute for fossil fuel burning in industrial facilities. Cement manufacturing plants are among the SRF end-users. SRF co-processing in cement kiln systems has been tested and evaluated for several years and has shown promising results. Cement companies intend further to improve the co-processing technology, considering the massive and increasing amount of solid waste generation, stringent environmental regulations, and economic benefits. SRF utilization in the cement industry has been experimented with using different tactics. Improving SRF characteristics through different pre-processing methods covers one side of this picture. Investigating the engineering and technical potential of SRF combustion in high-temperature cement kiln systems covers the other side. This review article provides a state-of-art description of SRF co-processing in cement manufacturing plants and discusses challenges in this area.

1. Introduction

Co-processing means using waste materials as a partial substitution of conventional fuels and/or raw materials in manufacturing processes for recovery of energy and/or resources (InforMEA., 2020). A circular economy allows the waste-to-energy system to strengthen and expand its role towards new or little developed value chains. Secondary fuel production and valorization of new waste streams in material recycling are examples (Lausselet et al., 2017). The high pace of urbanization and rapid industrialization have made effective solid waste management a significant social and economic need. Utilizing waste derived fuels in cement factories provides an environmentally sound waste management solution for urban local bodies. It also establishes a waste-to-energy chain towards a more circular economy. Waste co-processing is not a novel concept in the cement industry. Over the last forty years, the industry has had comprehensive experience in research, development, and application of different types of waste for energy production, such as municipal, industrial, commercial, hazardous, and agricultural wastes. These waste types have been successfully co-processed as alternative fuels in cement plants since the 1980 s. The concept was encouraged by the first oil crisis in the early 1970 s looking for ways to cut costs, but eventually it became a sustainable waste management concept, especially for tracking solid generation of waste in urban areas.

Today, waste co-processing in cement plants contributes significantly to promoting industrial symbiosis under the umbrella of the circular economy by providing a unique opportunity for energy recovery and waste management. However, the realization of this potential is still in the nascent stage. This study summarizes the potential of solid recovered fuels (SRF) as a co-processing ingredient in cement plants by presenting up-to-date information. The review is divided into three sections. The first section discusses the waste generation problem as a global crisis, and different waste categories are defined. A detailed overview of SRF is presented in the second section, including its pre-treatment methods and characterization. The third section provides prospects of cement kiln systems that can be used to co-combust SRF, followed by a discussion of some challenges related to such applications.

2. Waste – a global problem

Imagine the household waste generation on a day-to-day basis and the pressure you will have if the domestic garbage bin is overloaded due to a delay in the municipal waste collection system. This example is sufficient to understand the waste problem in today's life. According to a World Bank report by Kaza et al (Kaza et al., 2018)., the world generates 2 billion tonnes of municipal solid waste (MSW) annually, and

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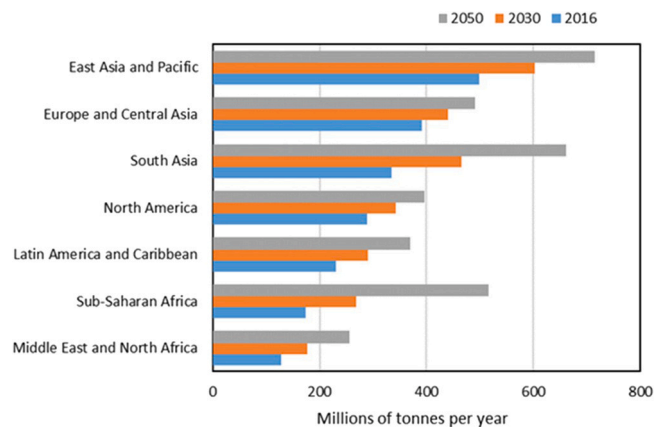 *E-mail address:* amila.c.kahawalage@usn.no (A.C. Kahawalage).

Fig. 1. Projected MSW generation by region; modified diagram based on (Kaza et al., 2018).

the waste generated per day averages 0.74 kg per person. Waste generation is generally expected to increase with economic development and population growth. Predictions from the same World Bank report (Kaza et al., 2018) indicate that global waste will have grown to 3.4 billion tonnes by 2050.

Fig. 1 shows a comparison of waste generation in 2016, classified according to different regions of the world, together with waste predictions in 2030 and 2050 in each region. Asia, Pacific, and Europe are the top three waste generators in 2016 and will be among the top four in the next thirty years. Sub-Saharan Africa, South Asia, Middle-East, and North Africa are considered fast-growing regions, and their current waste generation will be tripled, doubled, doubled, and doubled, respectively, by 2050. According to Kaza et al (Kaza et al., 2018). the amount of waste generated depends on the country's economy. Higher income countries generate about 34% of the total global waste, around 683 million tonnes annually. Low-income countries will generate more than three times the quantity they generate today by 2050. This increasing amount of waste in the next thirty years indicates the necessity of a structured and sustainable waste management solution across every region.

There is a considerable variation in the composition of MSW across different countries. As shown in Fig. 2(a), waste generation in the United States in 2018 (EPA, 2021), shows a scattered distribution among different types of waste. Their MSW mainly contains paper and cardboard, food waste, yard trimmings, and plastics. A similar scattered situation can be observed for the MSW in Brazil but varying composition (Fig. 2(b)). Brazil has reported 22 % of paper and cardboad, 13 % of plastic, 10 % of ferrous metal and 29 % of undefined waste (De Caevel and Michel, 2018). A different waste generation practice is observed in Shanghai, China, where food/kitchen waste amounts to 61%, followed by rubber and plastics (18%) and paper and cardboard wastes (12%), as shown in Fig. 2(c) (Ding et al., 2021). However, in general, significant components of MSW are food and green waste, plastic, paper, cardboard, metal, glass, rubber, leather, and wood. The main reasons for a diversified waste composition are income level, consumer preferences, climate, and weather conditions. Moreover, considering the global overview, the largest food and green waste category makes up 44% of the global waste; plastic, paper and glass amount to 12%, 17%, 4% and 2%, respectively (Kaza et al., 2018).

Currently, most of the global waste ends up in landfills. Kaza et al (Kaza et al., 2018). report that almost 40% of the waste is landfilled, whereas about 19% undergoes material recovery through recycling and composting, and 11% is treated through modern incineration. Fig. 3(a) illustrates different waste processing methods applied in different regions. It includes anaerobic digestion, waste incineration, composting, recycling, landfilling, and open dumping. Waste recycling preserves natural resources and energy while preventing pollution by reducing

the need to collect new raw materials. Landfilling and open dumping are the leading waste disposal methods in all the regions, as shown in Fig. 3(b). Latin American, Caribbean and Sub-Saharan countries landfill more than 93% of their waste, which indicates a serious environmental issue in those regions. Also other regions lack sustainable waste management practices. Less than 50% of their MSW are valorized. Today, governments increasingly recognize the risks and costs of dumpsites, and therefore pursue sustainable waste disposal methods.

2.1. Processing of municipal solid waste (MSW)

MSW collected as a "mixed waste" or "separated waste at the source of collection" is treated either mechanically, biologically, or chemically to recover valuable materials. Fig. 4 gives a general overview of MSW processing. Although a separate collection of organic, combustible and other wastes is promoted among the public, the effectiveness of the waste collection schemes cannot always be guaranteed. For example, if organic waste is mixed with other waste types, it is not easy to treat them by anaerobic digestion. A mechanical-biological treatment (MBT) system is a possible solution under such circumstances. It separates biodegradable waste fractions and recovers recyclables from mixed waste streams. This is done by combining mechanical separation of different waste types with biological stabilization of organic matter via processes such as anaerobic digestion or composting (Fei et al., 2018). MBT plants produce more output types, as shown in Fig. 4, compared to traditional treatment methods. The outputs are refuse-derived fuel (RDF), with a relatively high calorific value; a wet organic fraction which may undergo biological treatment; plastic; cardboard; ferrous and non-ferrous metals; and inert wastes which can be used for recycling. However, contaminated and hazardous industrial waste and infectious waste is not recommended for processing at MBT plants (Dilewski and Stretz, 2003). Specific waste fractions can be used for pyrolysis, where organic materials are thermochemically decomposed at high temperatures in the absence of oxygen or an atmosphere of inert gases. RDF, another output from MBT, has advantages over mixed MSW in terms of quality and uniformity and is therefore suitable for co-processing or incineration. RDF obtained after processes carried out in MBT plants has a higher calorific value, a greater content of combustible fractions and less moisture than MSW. These values indicate that RDF is a better fuel than MSW. Burning MSW entails a loss of the recyclable materials recovered in MBT plants, which contradicts the European waste policies (Montejo et al., 2011).

2.2. Conversion of waste into a fuel

Any material or substance that can be used as a fuel, other than fossil fuels (petroleum oil, coal, and natural gas), is alternative fuels, also known as non-conventional and advanced fuels. Some well-known alternative fuels include biodiesel, bio-alcohol, waste derived fuels, hydrogen, non-fossil methane, non-fossil natural gas, vegetable oil, and other biomass sources. These fuels have been applied for different energy-producing applications such as transportation, electricity production, and machine operation in the industry. Waste-to-Energy (WtE) plants use waste as a renewable fuel to co-produce electricity, heating and cooling for urban utilization. The World Business Council for Sustainable Development explains that "selected waste and by-products with recoverable calorific value can be used as fuels in a cement kiln, replacing a portion of conventional fossil fuels, like coal, if they meet strict specifications. Sometimes they can only be used after pre-processing to provide 'tailor-made' fuels for the cement process" (Group, 2018).

2.3. Types of waste derived fuels

Waste derived fuels include residues from MSW recycling facilities, industrial/trade waste, sewage sludge, industrial hazardous waste and biomass waste. Co-processed raw waste is less effective than using pre-
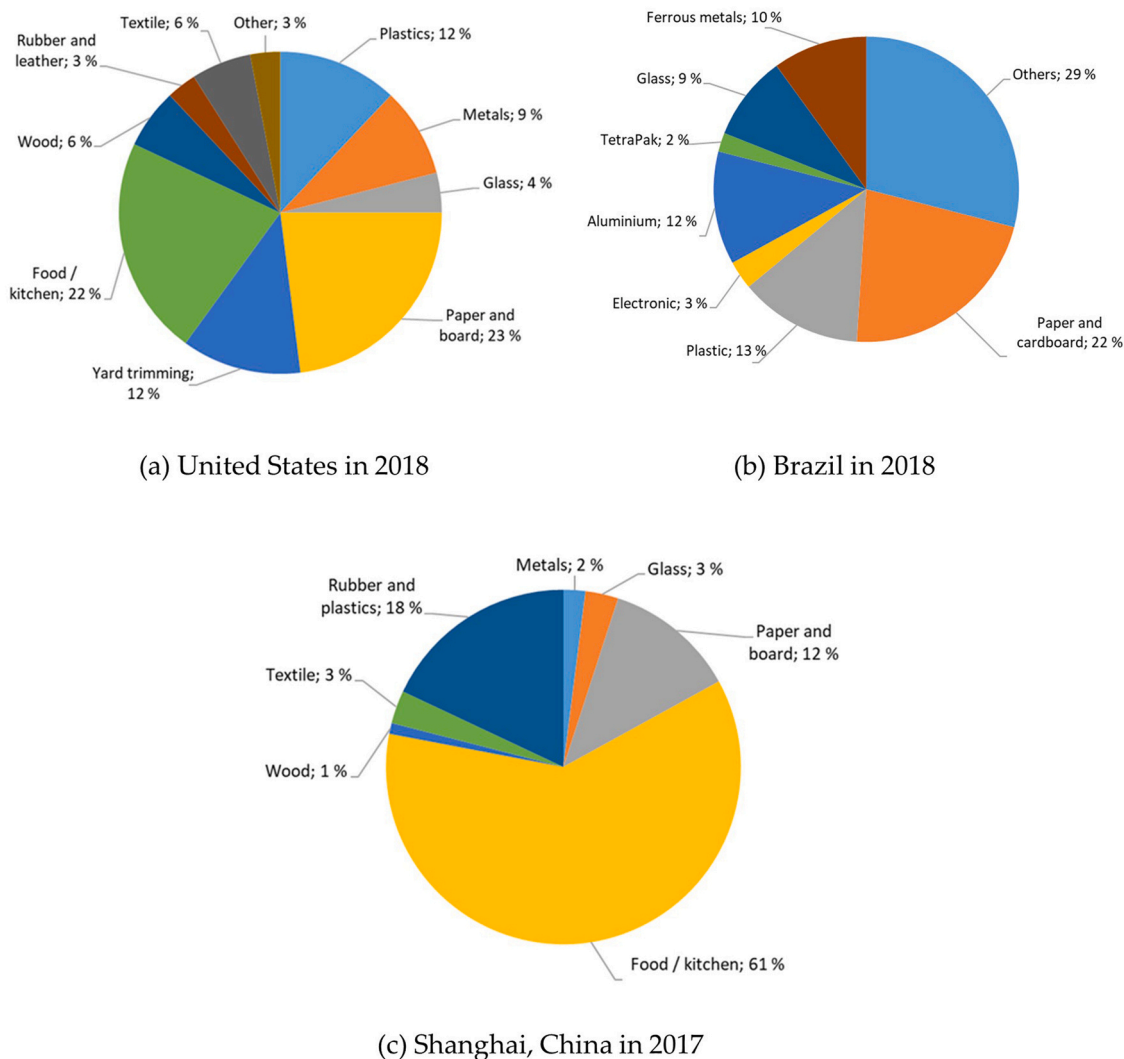
(a) United States in 2018

(b) Brazil in 2018

(c) Shanghai, China in 2017

Fig. 2. Composition of municipal solid waste in three different countries; (a) United States in 2018 (EPA, 2021), (b) Brazil in 2018 (De Caevel and Michel, 2018), (c) Shanghai, China in 2017 (Ding et al., 2021)

processed wastes because raw waste materials usually have a higher moisture content, lower calorific value, wider size distribution, and higher ash content. As a result, a multi-stage processing method is often applied to improve fuel qualities. RDF and SRF are waste products with increased calorific value, reduced moisture content, more homogeneous particle size, and reduced ferrous and non-ferrous metal content compared to raw MSW. SRF is a fuel produced from RDF. In SRF, the quality is known and defined according to a standard procedure (see section 2.6). Other terms are also used for MSW-derived fuels such as Recovered Fuel (REF), Packaging Derived Fuels (PDF), Paper and Plastic Fraction (PPF), and Process Engineered Fuel (PEF). REF, PDF, PPF, and PEF usually refer to source-separated, processed, dry combustible MSW fractions (e.g., plastics and/or paper) which are too contaminated to be recycled. They have a higher calorific value, lower moisture content, and lower ash content than RDF derived from mixed waste fractions.

Fuel analyses of fossil fuels and some of the commonly used alternative fuels are presented in Table 1. These tabulated values reflect the diversity of these fuels. The most noticeable differences between alternative and fossil fuels can be identified by these analyses, which must be addressed technically when substituting fossil fuel burning in cement kilns and precalciners with alternative fuels. These differences may significantly affect combustion and cement production. The presented values are approximate and may deviate depending on factors such as source, weather conditions, pre-processing methods efficiency

and storage conditions. The volatile content of alternative fuels such as pinewood, rice husk, MBM, and RDF is higher than in conventional fuels. These components are readily burnt in the presence of oxygen. Volatile matter is one of the factors governing the ignition and flame stability, the reactivity and burnout of chars, and the amount of unburned carbon in the fly ash. It also determines the required shredding fineness (Miller, 2013). A higher content of volatile matters makes the fuel easier to ignite.

The ash content of some alternative fuels is higher than in fossil fuels, and this is one of the factors that may cause operational problems in the system. The ash introduces new elements, which can combine with clinker minerals and change the clinker chemistry. The fixed carbon content gives information on the amount of char formation in the thermochemical conversion process. The alternative fuels mentioned here, show a lower fixed carbon content than fossil fuels. The main drawback of alternative fuels is the higher moisture content. As a result, some energy is consumed for water evaporation, increasing the combustion time while decreasing the process efficiency and production capacity.

Among the minor elements presented, the most influencing elements are sulfur and chlorine. It is reported that the sulfur content decreases the alite content and stabilises belite and free lime (Engelsen, 2007). An excessive chlorine content in the cement clinker may cause corrosion problems, and therefore a chlorine limit has been specified
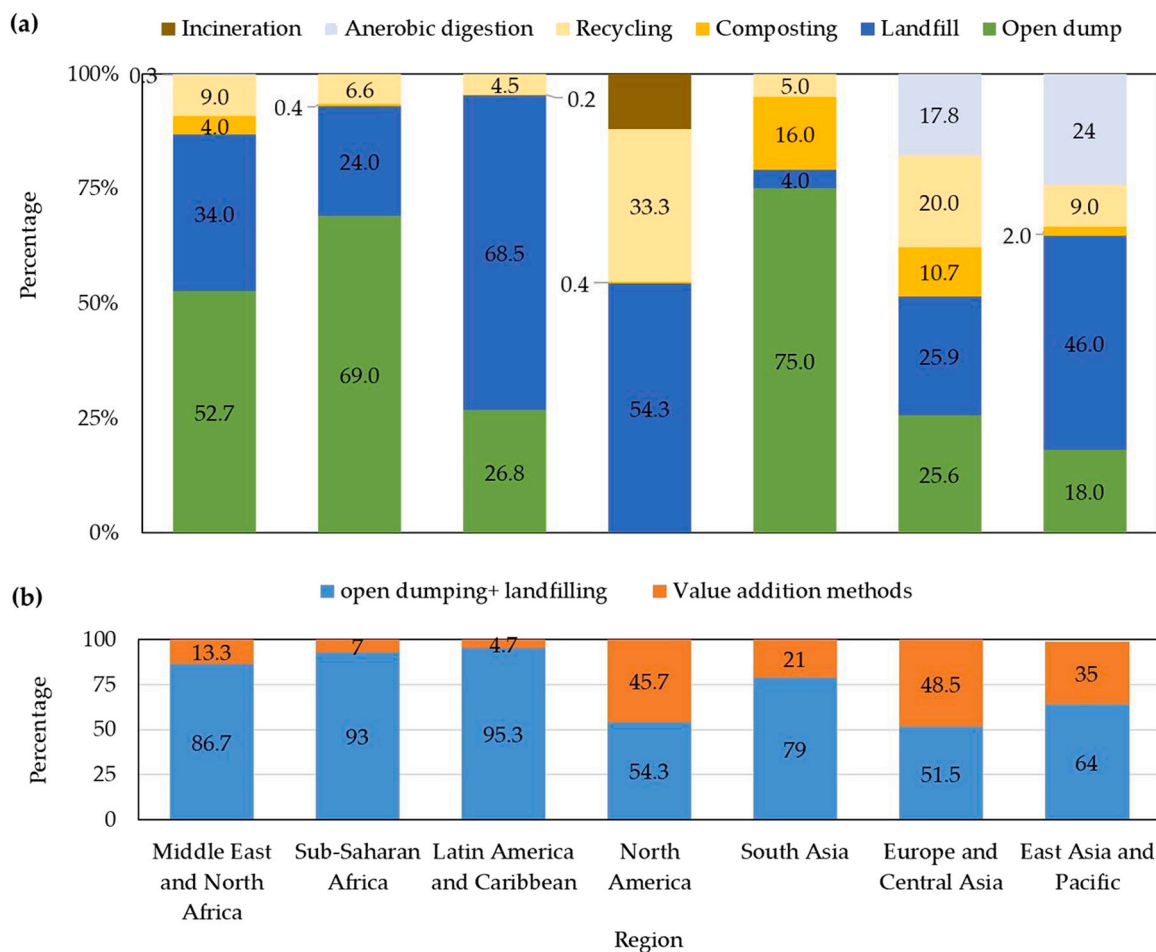
(a)

(b)

Fig. 3. Waste disposal methods by region; modified diagram based on (Kaza et al., 2018).

(Mohamed Yousri et al., 2020). Both SRF and RDF show higher chlorine content and lower sulfur content than coal and petcoke. Only small additions of selected elements often referred to as foreign ions, can extensively alter the melt properties. The overall clinker reactivity is increased by alkalis such as Na and K.

The heating value of alternative fuels that are available in large quantities, such as RDF, is significantly lower than typical fossil fuels because of the higher ash and moisture content and the differences in chemical composition. As a result, co-processing of these alternative fuels must be maintained at higher mass flow rates to provide the same thermal input the conventional fuel provides. Increased mass flow can also increase the volume flow proportionally, if the fuel density is low, thus creating fuel feeding problems during plant operation.

2.4. Definition of RDF

Although the concept of RDF has existed since the early 1970 s (Daugherty, 1986), there is still ambiguity about an ideal definition of RDF. The simplest definition is that RDF is a heterogeneous fuel mixture produced from the combustible components of MSW. The UK Environment Agency defines RDF as a fuel produced from residual waste that meets an end-user contractual specification for energy recovery from the waste facility (Holder, 2015).

RDF covers a wide range of waste materials that have been processed to fulfill industry specifications mainly to achieve a higher calorific value than normal MSW. The RDF definition results from variations in composition and quality in RDF coming from different MSW processing plants, RDF used in industrial plants, and RDF used in

research experiments. In daily practice, many calorific wastes are referred to as RDF, and their compositional quality and environmental parameters are often not well described. This poses a risk and uncertainty for human health and the environment. In some research articles, RDF and SRF terms describe the same experimental waste sample. Due to lack of resources and unawareness of negative impacts, the RDF quality is often not checked multiple times during the same research experiments and plant trials. Instead, a quality check performed once is assumed to be same for all cases. These assumptions may tend to give the wrong conclusions, which can be harmful to both the process and the environment.

An easy way to understand the definition of RDF is comparing it with SRF since SRF has a standard procedure for production. The original source of SRF and RDF is the non-hazardous waste fraction of MSW. Fig. 5 provides a schematic diagram to differentiate between RDF and SRF (Martignon, 2020). The main requirement is that SRF is specified and classified by a defined international or local standard, must be accompanied by a self-declaration, and may also require external certification depending on the customer. In 2003, CEN, the European Committee for Standardization, established a technical committee, the CEN/TC 343, which developed the "European Standard EN 15359 Solid recovered fuels –Specification and Classes" (Standardization, 2003). Flamme and Geiping (Flamme and Geiping, 2012) present the basic principles of quality assurance for SRF, development of the German RAL Quality Assurance System, and additional specifications that have emerged from the European standardization work of CEN/TC 343. They elaborate that a consistent quality standard and reliable quality assurance are required when SRF is used for energy recovery in industrial plants.
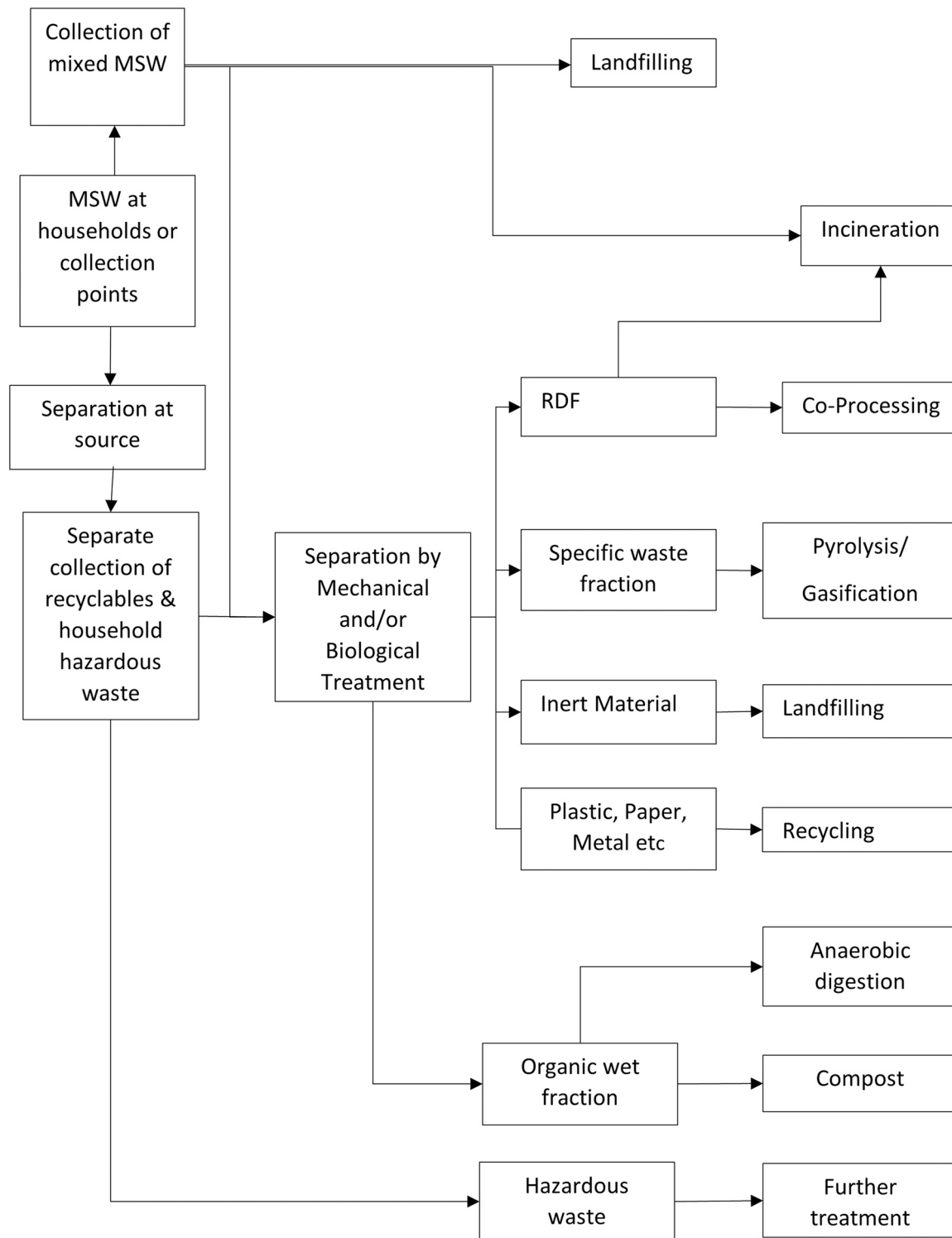
Fig. 4. Overview of MSW material flow and its different utilization and treatment options; modified diagram based on a study by Mutz et al (Mutz et al., 2017).

2.5. RDF and SRF production

Fig. 6 presents a comparison of ten different countries in Europe based on the production and consumption of RDF, where Germany has the largest quantity of production and use of RDF. England produces more than thirty times the quantity it uses and has the highest RDF export market in the world (Fig. 7). The Netherlands and Austria use more RDF than their own production quantity. In Europe, non-standardized RDF is mainly intended for dedicated heat-oriented

installations and district heating, and standardized SRF is used for cement kilns and coal-fired plants (De Caevel and Michel, 2018). According to Brown (Brown, 2016), 11 countries of the Northern Cluster have a combined 104 million tpa of effective residual waste treatment capacity, either operating, under construction, or committed. This capacity is made up of 383 dedicated energy-from-waste incineration facilities, 13 advanced conversion technology (ACT) facilities, 103 pretreatment facilities using either MBT or autoclave technologies, 73 industrial emissions directive (IED) compliant biomass facilities,

Table 1
Comparison of fossil fuels and alternative fuels according to proximate analysis, ultimate analysis and lower heating value (LHV) (Cortada Mut, 2014).

	Fuel	Proximate analysis [wt% dry]				Ultimate analysis [wt% dry]								LHV (MJ/kg)	Ref.
		Moisture	Volatile matter	Fixed carbon	Ash	C	H	N	O	Cl	S	Na	K		
Fossil fuels	Anthracite coal	5.06	1.7–11.0	67–98	3.8–20.0	64–87	0.4–3.4	0.2–1.5	0.7–2.2	300–380*	0.7–2.2	0.09–2.-9[a]	0.29–4.15[#]	30.23–34.89	(Zhang et al., 2015; Singer et al., 1981; AFPM, 2012; Milenkova et al., 2003; Energy, U.D.o, 2012; Tsubouchi et al., 2005; Vassilev et al., 2010; Weston, 1992; Zevenhoven and Kilpinen, 2005)
	Bituminous coal	4.44	14–40	33–86	3.7–12.0	55–85	3.8–5.9	1.0–2.0	1.8–13.-0	100–340*	0.3–4.3			19.77–34.89	
	Lignite coal	17.75	26–47	29–40	4.2–18.0	42–65	2.8–6.2	0.7–1.6	12–31.0	100–140*	0.5–6.7			9.30–19.30	
	Petcoke	0.21–0.28	10–20.0	71–88	0.2–3.0	81–90	3.1–3.7-0	0.9–1.7	0.8–4.3	~0	2.9–7.4	40–70*	20–50*	29.5–34.0	(Singer et al., 1981; AFPM, 2012; Milenkova et al., 2003; Energy, U.D.o, 2012; Birghila and Popovici, 2013)
	Crude oil	-	n.a.	n.a.	~0	81–87	10–15	n.a.	0–3.8	~0	0–5.7	n.a.	n.a.	39–42.7	(Energy, U.D.o, 2012; Co, 2007)
	Natural gas	-	100.00	0.00	0.00	65–75	20–24	0–1.5	0–1.5	~0	0–10	n.a.	n.a.	46.8–53.8	(Weston, 1992; Zevenhoven and

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Table 1 (continued)

Fuel		Proximate analysis [wt% dry]				Ultimate analysis [wt% dry]								LHV (MJ/kg)	Ref.
		Moisture	Volatile matter	Fixed carbon	Ash	C	H	N	O	Cl	S	Na	K		
Alternative fuels															Kilpinen, 2005
	Pine wood	8.4	79–83	15–17	0.3–0.5	49–51	5.8–6.0	0.1–5.9	36–44	< 0.1	~ 0	n.a.	~ 1000 *	19.7–19.8[a]	(Weston, 1992; Hassan el et al., 2009)
	Straw	1.5	64.3–80.5	13–19.5	4.7–20.1	46–50	5.6–6.4	0.5–2.1	40.1–44.6	0.60	0.20	0.16–3.-5[#]	12.6–38.5[#]	18.1[a]	(Vassilev et al., 2010; Motasemi et al., 2015; Stenseng, 2001; Bioenergy, 2021)
	Rice husks		61–69	16–17	15–20	38–42	3.0–4.8	0.4–0.6	36–54	n.a.	0.1–0.2	0.10	2.20	15.4[a]	(Bioenergy, 2021; Várhegyi et al., 2011)
	SRF	17–30.3	70.80	13.2	8.90	54.70	7.70	0.70	36.70	0.41	0.18	0.14	0.09	23.20	(Wilén, 2004)
	Tire derived fuel (TDF)	2.58	57	33.34	7	64–81	5.6–7.2	0.3–0.5	2.0–6.0	0.2–2	1.4–1.6	~ 0	~ 0	31–32.8	(Weston, 1992; Unapumnuk et al., 2006; Larsen, 2007; Chinyama and Lockwood, 2007)
	Meat and bone meal (MBM)	4	65–72	7.2–9.7	18–28	42–46	5.8–6.4	7.5–11.-0	15–38	0.4–0.6	0.4–1.0	0.31	0.10	16.2–19.9	(Ariyaratne et al., 2011; Aho and Ferrer, 2005; Ayllón et al., 2006; Kääntee et al., 2004)
	Polyethylene	0	100.00	~ 0	~ 0	86.00	14.00	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0	40.2–44.2	(Panagiotou and Levendis, 1994; Wang
	Poly-vinyl-chloride		91.00	9.00	1.00	36.00	5.00	~ 0	~ 0	57.00	~ 0	~ 0	~ 0	19.20	

Table 1 (*continued*)

Fuel	Proximate analysis [wt% dry]				Ultimate analysis [wt% dry]								LHV (MJ/kg)	Ref.
	Moisture	Volatile matter	Fixed carbon	Ash	C	H	N	O	Cl	S	Na	K		
Sewage sludge	75	48–64	0–6	17–50	28–39	3.8–4.1	3.8–4.3	29–36	0.1–0.8	~1	0.20	0.60	14.0–19.1	et al., 2004 (Bioenergy, 2021; Shah et al., 2020)

a lower heating value calculated from the higher heating value, *Concentration in ppm weight dry basis, #Chemical ash composition as wt% Na_2O and K_2O, n.a.: not available

including facilities already co-firing residual waste, and 102 cement kilns capable of processing SRF. SRF co-processing in European cement factories has a gap to close between lab/pilot scale experiments and continuous industrial use. Countries such as Germany, Austria, Belgium and Norway show encouraging opportunities during the last couple of decades (Brown, 2016; Tokheim, 2006; Tokheim and Brevik, 2007).

One of the main reasons for this gap is the lack of standardization of RDF. RDF tested and optimized for one cement factory may not be the optimum setting for another, because cement factories have different specifications (e.g., geometry, production units, raw materials and production scale). Although several technical feasibility studies have been conducted on RDF co-processing in cement plants, differences in physical and chemical characteristics of RDF affect the results of these studies, which creates a barrier to reasonably compare them to each other. Studies which explain co-processing of SRF show lower challenges in this respect since their qualities are specified and standardized locally or regionally (De Caevel and Michel, 2018).

2.6. Characterization of SRF

Characterization of SRF plays an essential role because it determines the correct classification, production, and application methods for SRF. These characteristics reveal chemical, physical, and biological features of SRF that are useful in deciding end-user applications. These parameters are; grain or particle size, net calorific value, chlorine content, sulfur content, fluorine content, ash content, moisture content, biogenic carbon content, bulk density and heavy metals content such as As, Sb, Pb, Cd, Cr, Co, Cu, Zn, Ni, Hg, Tl, V, Sn and Mn.

Chlorine is a crucial element causing high-temperature corrosion in waste-to-energy plants. A high chlorine concentration stimulates the formation of eutectics in fly ashes with a relatively low melting point during combustion (Ma et al., 2010). The knowledge about the total chlorine content as well as differentiation in organic chlorine compounds and inorganic chloride salts are significant in improving the prediction of combustion. Organic chlorine in SRF and MSW mainly originates from packaging waste (PVC), and inorganic chlorine comes from alkali metal chlorides, e.g. NaCl, MgCl2, KCl and CaCl2 (Ma and Rotter, 2008). Krawczyk et al (Krawczyk et al., 2018). conclude that chlorine plays a significant role in the CWU structure (approximately 87%). In this study, the total nuisance index (CWU) was calculated as the sum of individual harmfulness of the fuel component. They also show that removing the PVC from the SRF could reduce chlorine content by up to 70%. This may be implemented by optical separation of PVC during the preparation of SRF.

Limit values of three important fuel characteristics are included in the SRF classification process: net calorific value (NCV), chlorine content (Cl) and mercury content (Hg). Each of the classification characteristics is split up into five classes, depending on value of NCV, Cl content and Hg content (Table 2). When the class number increases, the SRF quality is reduced. Finally, the SRF class code is defined from a combination of these three classes (ISO ,2021).

3. Cement manufacturing and co-processing of SRF

In the IEA roadmap describing the cement industry's low carbon transition strategies, waste co-processing is prioritized above incineration and landfilling to deploy a circular cement economy (IEA, 2018). The main reason for such recommendations is the increasing demand for cement and concrete and the increase in waste generation as a result of population growth.

The demand for concrete is growing proportional to the increased need for domestic, public and commercial infrastructure facilities and the increasing population growth. Today, China is the world's largest cement producer and holds more than 50% of the production share, while India shares the second position. The global cement production amounted to an estimated 4.1 billion tonnes in 2020. Twenty-five years
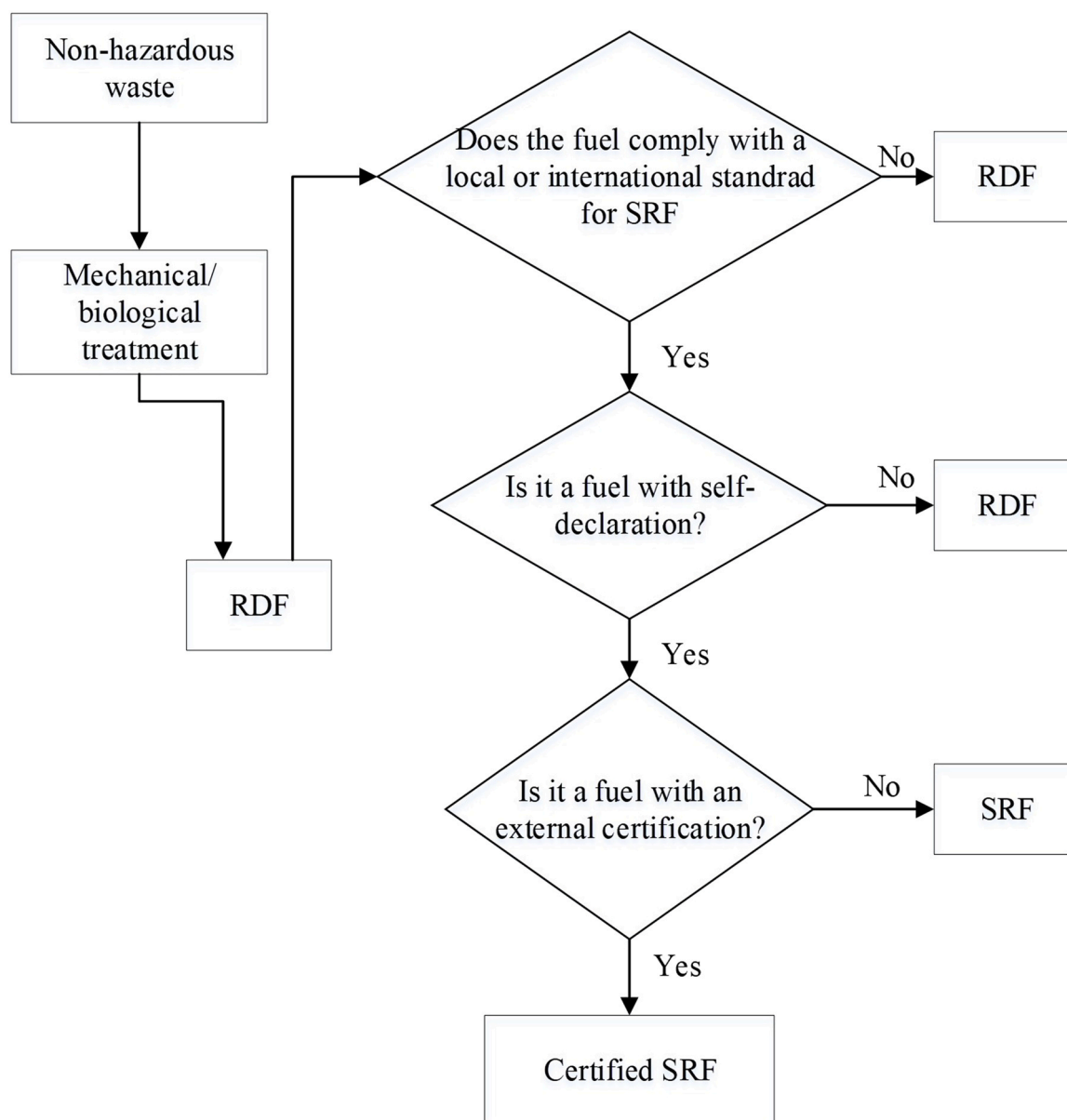
Fig. 5. Schematic approach to distinguish between RDF and SRF; modified diagram based on (Martignon, 2020).

ago, this production was just 1.35 billion tonnes (Garside, 2021). In 2018, the largest cement company worldwide based on production capacity was LafargeHolcim, which had a capacity of 367 million metric tonnes that year (Statista, 2018). Fig. 8 describes the projected cement production until 2050. The cement industry plays a crucial role in the energy sector, being the third-largest industrial energy consumer, comprising 7% of the global industrial energy use (10.7 EJ) and representing 7% of the total CO_2 emissions (IEA, 2018).

Cement production involves the decomposition of limestone (calcium carbonate), which shares about two-thirds of the total CO_2 emissions generated in the process, with the remainder of CO_2 emissions resulting from the combustion of fuels. Considerable progress in energy efficiency and the use of alternative fuels and clinker replacements have always been an intense topic for governments and cement manufacturers. Alternative fuel use in the global cement industry corresponded to 5.6% of the thermal energy in 2014. According to the International Energy Agency (IEA), this value must be increased to 17.5% to align with the IEA reference technology scenario (RTS) and to 30% to comply with the 2 degrees celsius scenario (2DS) (IEA, 2018).

3.1. Alternative fuel use in the cement industry

Fig. 9 illustrates the global tendency towards alternative fuel usage in the cement industry across 17 countries (or group of countries) in 2017 (Industry, 2019). On average, the global cement industry has fulfilled 18% of its thermal energy requirement by alternative fuels. European countries reported a higher share of this energy whereas Austria, Czech Republic, Germany, and Poland could fulfill more than 60% of their total thermal energy using alternative fuels. Even though alternative fuel sources are diversified across the world, developing countries such as India, the Philippines, Thailand, and African countries have very little use of alternative fuels in their local cement production facilities.

The composition of the energy used in the US cement industry has changed appreciably from 1996 to 2016, as shown in Fig. 10. Coal and coke, which were once the dominant fuels, have dropped from 74% to 57%. Waste fuel use was increased slightly from 5.5% to 6.8%, but alternative fuel use was increased from 2% to 8.3% in US cement plants. The alternative fuel use in 1996 represented just 2% of the energy consumption in cement plants, but by 2016, it was quadrupled.
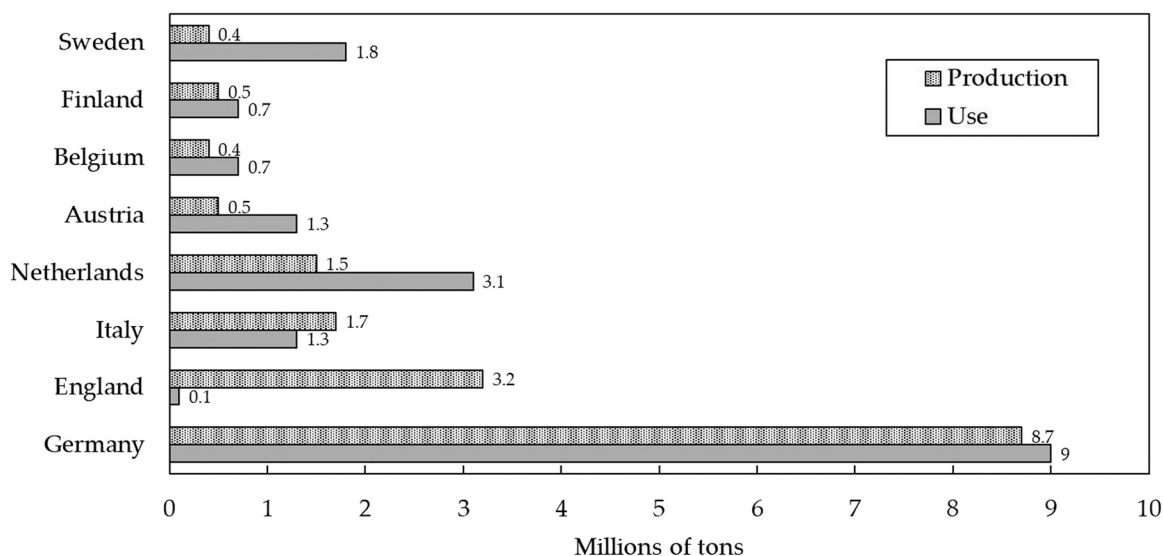
Fig. 6. Comparison of RDF quantities produced and used in some European countries; data from each country (2008–2016); modified diagram based on (De Caevel and Michel, 2018).
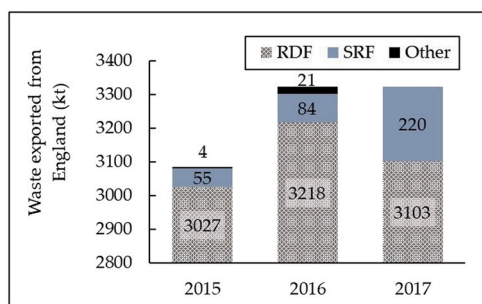

Fig. 7. Comparison of RDF and SRF production in England (CIWM Presidential Report, 2018).

3.2. The cement manufacturing process

Cement production processes can be categorized as dry, semi-dry, and wet processes, depending on the handling of the raw material before it is fed to the rotary kiln. Nowadays, almost all new plants are based on the dry process, and many old wet plants are also remodeled to dry or semi-dry processes. Dry cement manufacturing has three fundamental stages; grinding of raw materials into raw meal, producing clinker by pyro-processing the raw feed, and grinding of clinker and additives into cement. Fig. 11 provides an overview of the different processes in a representative dry-based cement plant.

First, raw materials are powdered by crushing and grinding and then homogenized to impair raw material quality differences. The raw materials typically consist of 80–90% limestone, 10–15% clay or chalk, and some silica, alumina, and iron ore.

The raw meal is then preheated to 750 ˚C and sent to the precalciner (also called calciner) where the chemical decomposition of limestone ($CaCO_3$) into lime (CaO) and carbon dioxide is initiated and extended up to a calcination degree of about 90%. The precalciner is located between the preheater and the rotary kiln. The exothermic process of fuel combustion and the endothermic process of carbonate decomposition in the raw meal is carried out rapidly in the precalciner. The precalciner and rotary kiln in modern cement systems provide feeding locations to waste fuel, as marked in Fig. 11. The precalciner provides a high-efficiency direct combustion solid-gas heat exchange where it disperses and suspends cement raw meal powder in a gas, making fuel combustion and calcium carbonate decomposition happen in a short time.

The precalcined meal enters the rotary kiln, where fuel is fired directly from the other end. First, the remaining (~10%) decarbonization of the meal occurs, and then the temperature gradually increases as the material slides and tumbles through increasingly hotter zones. Different clinker materials (alite, belite, aluminate and ferrite phases) are formed, and the solids will gain a temperature of up to 1450 ˚C (Li et al., 2020). Different fuels may be used in the rotary kiln burner, but usually a significant amount of pulverized coal is necessary to maintain a sufficiently high temperature in the burning zone and thereby facilitate the required chemical reactions. An intermediate product termed clinker is produced and allowed to leave the kiln.

The red-hot clinker is discharged from the end of the kiln and passes through a cooler to partially recover its thermal energy and reach a lower clinker handling temperature (about 100 ˚C). Ambient air is blown through the hot clinker bed. The hot air from the recuperation zone is used as combustion air in the rotary kiln (termed secondary air) and in the precalciner (termed tertiary air). The remaining air, exiting
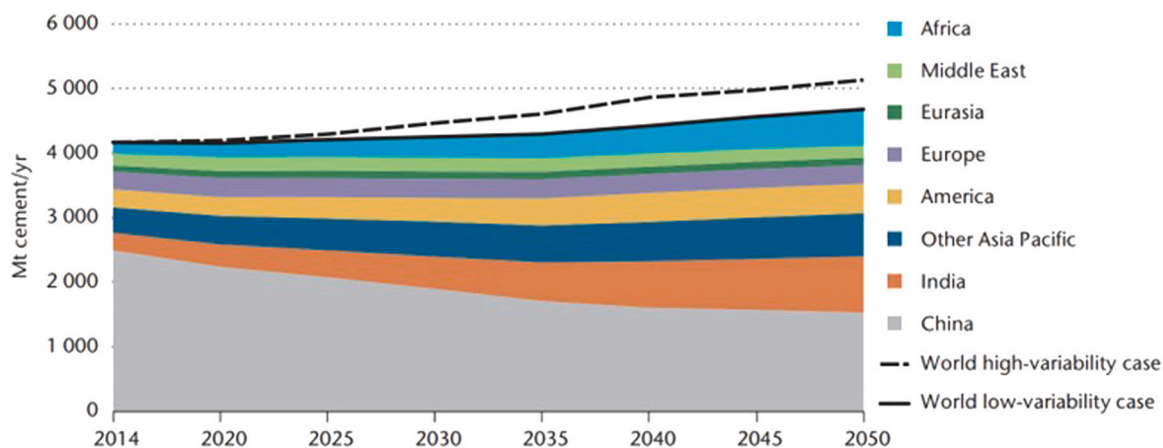
Table 2
Classification for solid recovered fuels (ISO, 2021).

Classification characteristic	Statistical measure	Unit	Classes				
			1	2	3	4	5
Net calorific value (NCV)	Mean	MJ/kg	≥ 25	≥ 20	≥ 15	≥ 10	≥ 3
Chlorine (Cl)	Mean	% in mass	≤ 0.2	≤ 0.6	≤ 1	≤ 1.5	≤ 3
Mercury (Hg)	Mean	mg/MJ	≤ 0.02	≤ 0.03	≤ 0.05	≤ 0.1	≤ 0.15
	80th percentile	mg/MJ	≤ 0.04	≤ 0.06	≤ 0.10	≤ 0.2	≤ 0.3

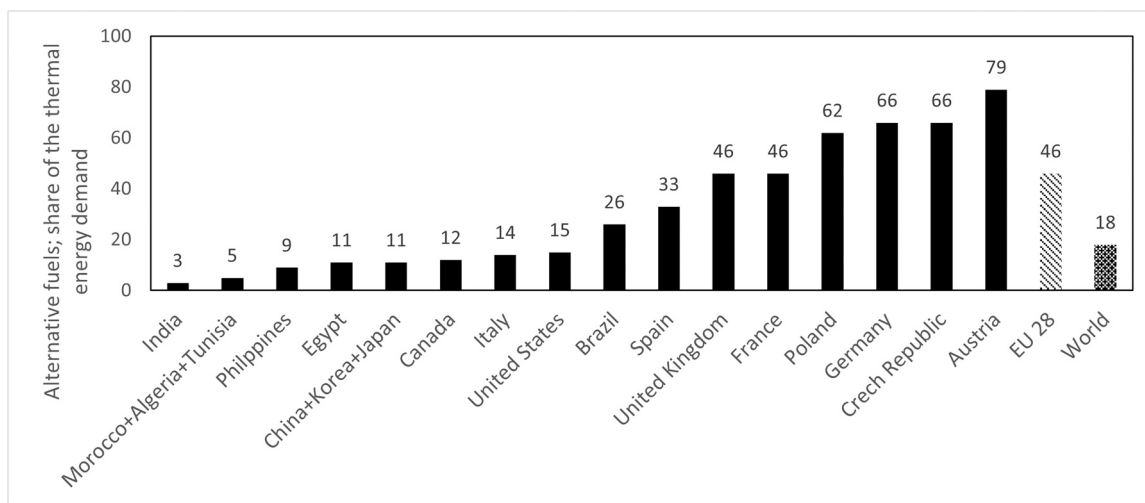**Fig. 8.** World cement production (IEA, 2018).

Fig. 9. Alternative fuel share as a percentage of total thermal energy demand in the cement industry in 2017; modified figure based on a report by the Association of the Austrian Cement Industry (Industry, 2019).
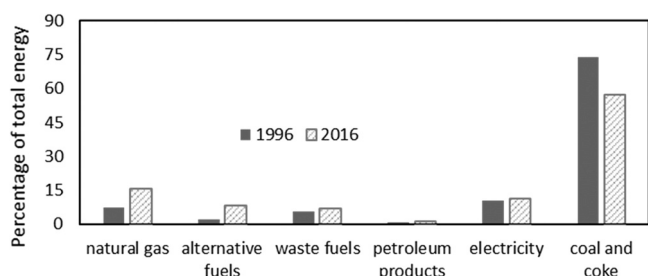

Fig. 10. Share of total energy in the US cement industry according to fuel type in 1996 and 2016 (Rick Bohan, 2019).

from the cold end of the cooler (cooler vent air), is sent to the stack after dedusting, typically applying an electrostatic precipitator. Then the cooled clinker is transferred to a storage silo, where it is intermediately stored before being used in the cement grinding process.

3.3. Cement kiln and precalciner as destinations for SRF

Using SRF in cement kilns and precalciners is a good solution both for waste producers, urged to find a proper final destination for the produced material, and for cement plant operators, who want to have a good production economy, optimal production energy allocation, and limited

environmental impacts. Potential waste feeding locations for dry kilns are i) the main burner at the rotary kiln outlet end, ii) a feed chute at the transition chamber at the rotary kiln inlet end (for lumpy fuels), iii) a separate burner in the riser duct between the kiln inlet and the pre-calciner, iv) a feed chute in the precalciner (for lumpy fuels) and v) a separate precalciner burner. For the case of long wet and dry kilns, a mid kiln valve may also be applied (for lumpy fuels) (Pollutants, 2007).

During combustion, solid particles interact with the surrounding gas exchanging heat and mass. Fig. 12 shows the basics of solid-gas reactions when a solid fuel particle is burned in a gas stream. Evaporation of moisture, devolatilization, char gasification and char combustion are dominant phenomena that determine the combustion characteristics in the gas-solid suspension. Physical changes of solid particles such as expansion/shrinkage and generation of internal pores occur. Moisture is removed by drying the particles. Released volatiles are oxidized and provide a heat source to the medium.

Fig. 13 illustrates different zones in a typical cement rotary kiln. It shows how the solids temperature gradually increase in the preheater tower via the calciner to the rotary kiln. The rotary kiln aims to create an environment promoting the chemical clinker reactions and noduli-sation. It provides heat for the clinker reactions and a high degree of fuel burnout so that no negative impacts on clinker quality or emissions occur. The precalciner decomposes calcium carbonate into calcium oxide while at the same time promoting sufficient fuel conversion to avoid pollutant emissions.
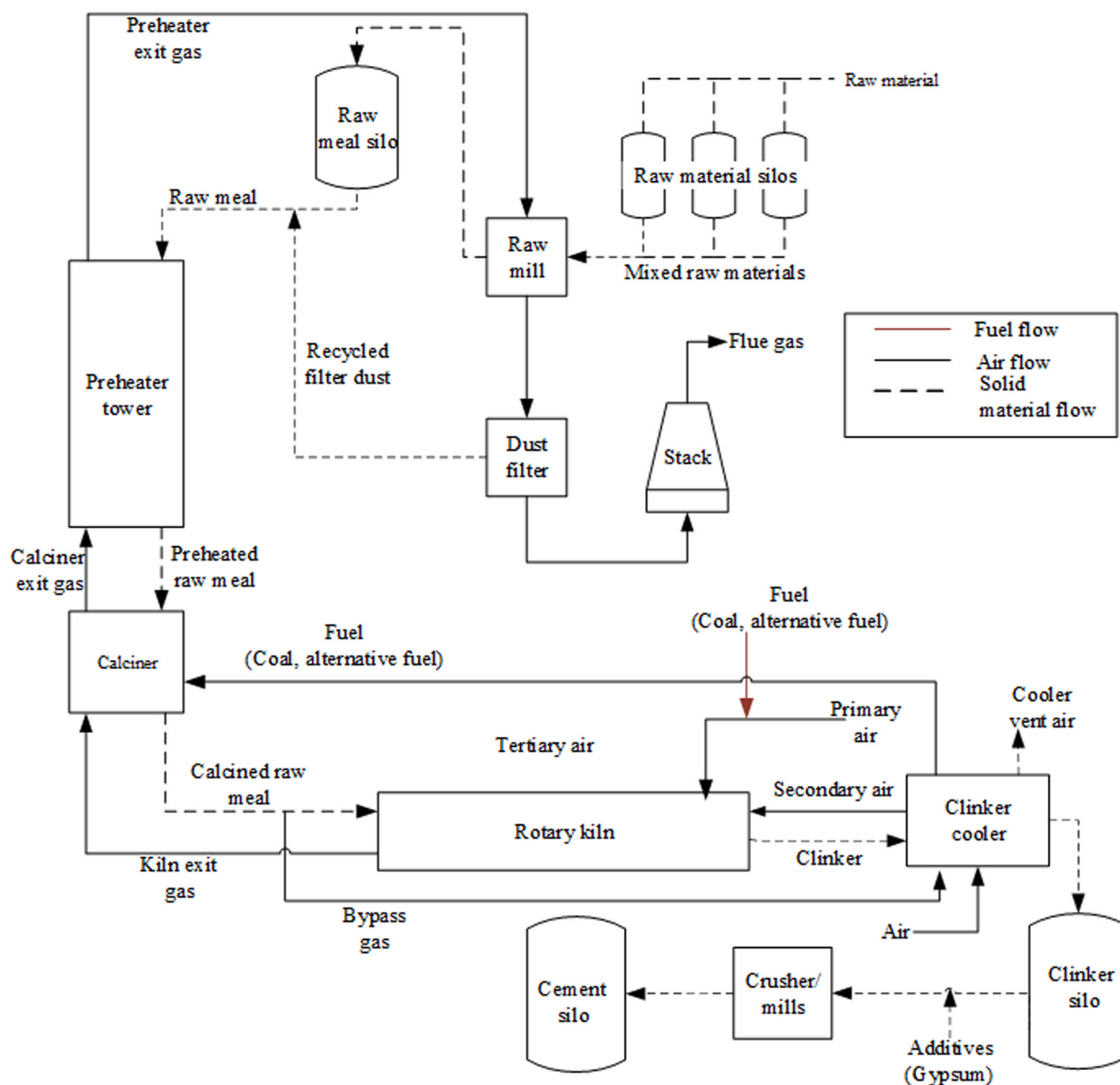
Fig. 11. Process flow sheet of a cement plant.

Most modern precalciner systems are designed according to the fuel used or other specific requirements. Four calciner designs can be distinguished: 1) Extended riser duct calciner 2) Separate-line calciner 3) In-line calciner (with staged combustion) and 4) In-line calciner with separate combustion chamber (GmbH, 2016). The combustion characteristics of solid fuel particles and liquid droplets in the precalciner are very different from those in the rotary kiln, because they burn in suspension showing single-particle behavior (Larsen, 2007).

A typical rotary kiln burner is of the non-premixed type (Singer et al., 1981), where fuel and transport air are delivered somewhere in the center of the burner, while the remaining combustion air is mixed gradually into this fuel stream. Typically, gas temperatures in the rotary kiln vary from a gas inlet temperature of 850–1100 °C up to 1700–2000 °C in the hottest parts of the flame, then decrease to about 900–1100 °C in the rotary kiln gas outlet end (Bye, 1999). The material residence time in the rotary kiln of a precalciner process is typically

30 min (Moir, 2003). The gas temperatures in modern calciner systems range from 800° to 900°C up 1150–1200 °C, depending on the calciner design.

Since the invention of the rotary kiln in 1873, significant design refinements have been made throughout the 20th century. Rotary kilns account for virtually all the cement made today (100% of the US production) (Oss, 2005). Rotary kilns consist of enormous, gently inclined, and slowly rotating steel tubes lined with refractory bricks. It is said that rotary kilns are the most significant pieces of moving manufacturing equipment in existence. Kiln dimensions can vary from 2 to 6 m in diameter and 50–225 m in length. The longer kiln section provides a sufficiently long residence time for complete decomposition of organic matter, a stable incineration state, high burning temperature and neutralization of acid waste gas (Zhang et al., 2019).

Cement rotary kiln co-processing of fossil and alternative fuels can effectively fix several heavy metals (Zhang et al., 2009). The hydration
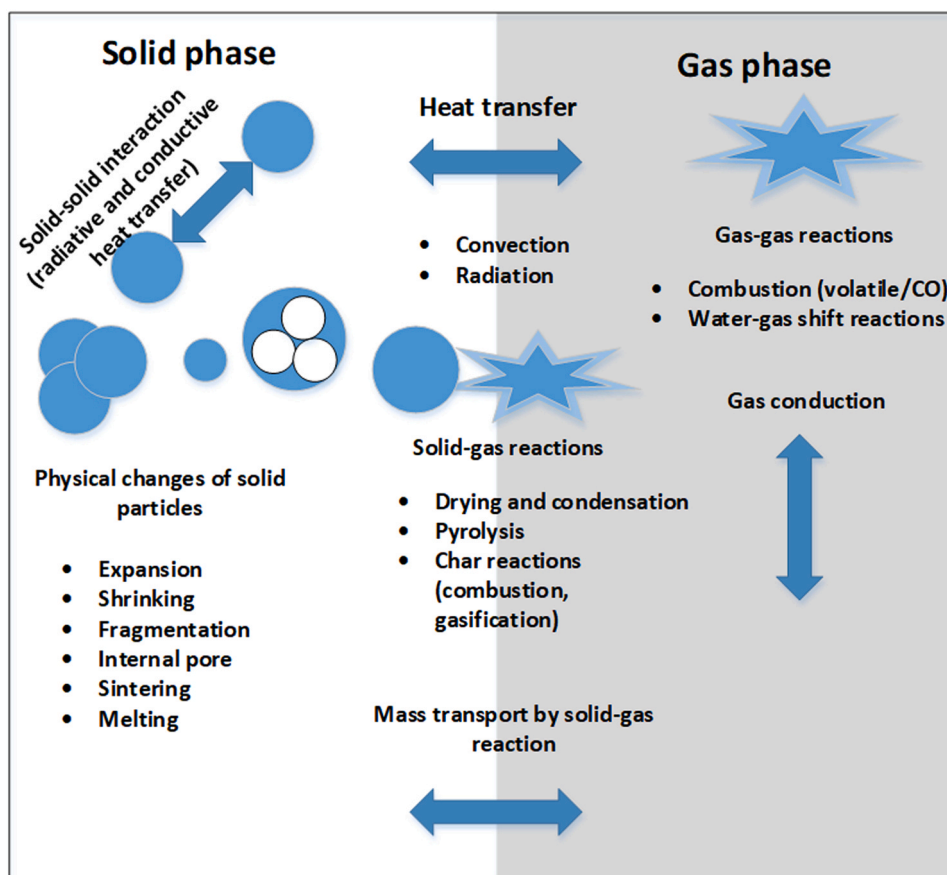
Fig. 12. Solid-gas reactions during combustion of solid fuel particles; modified diagram based on (Yang et al., 2004).

that follows during cement and concrete applications can fix for example As, Cd, Pb, and Zn and thereby decrease the release to the environment, making a positive attribute for co-processing of wastes with heavy metals in cement kilns. According to regular measurements since 2011, by Huaxin Environment Engineering Co., LTD, the dioxins concentrations in emissions from kilns co-processing RDF were reported to be far below the international limit of 0.1 ng TEQ/Nm^3 (Li et al., 2012).

3.4. Significance of fuel characteristics of SRF for co-processing in cement kilns

Knowledge about the calorific, chemical, biological and mechanical properties of RDF can be used to assess the combustion properties of SRF and to predict its suitability for industrial applications. Properties of SRF, analyzed by different methods are listed in Table 3.

The heating value and proximate analysis are the minimum prerequisites to assess the thermal recovery behavior and performance of the fuel. The heating value specifies how much heat is released (at standard temperature and pressure) when the fuel is completely combusted. The proximate analysis gives the quantity of moisture, volatile matter, fixed carbon and ash in the fuel.

The ultimate analysis is more expensive than the proximate analysis and gives the content of selected elements typically carbon (C), hydrogen (H), oxygen (O), sulfur (S) and nitrogen (N), in addition to ash and moisture. This makes it possible to calculate the stoichiometric air demand of the fuel and the amount of flue gas generated. This is crucial information to have when sizing the process equipment.

Some of the properties mentioned in Table 3 (Velis et al., 2010) are critical; for example, characterization of the reaction-related properties,

especially for co-combustion applications. Properties like storage stability are time-consuming to measure. High temporal variability and heterogeneity are major technical challenges when characterizing SRF and can be minimized by a proper sampling plan (Lorber et al., 2012).

As mentioned in Section 2.6, SRF has highly fluctuating properties, and the combustion of secondary fuels such as SRF is heavily dependent on those properties, i.e., moisture content, physical properties, particle characteristics, chemical composition, and homogeneity. SRF needs a longer residence time because of the larger particle size and the higher moisture content. Hence, a significant amount of energy is required to heat and dry the fuel particles. When the fuel particle is larger, the required residence time increases because water needs to be transported to the fuel particle surface for drying.

The physical nature of SRF, such as density, material structure, and surface texture, also play a vital role in combustion. Particles with a high density have lower suspendability in a gas stream, and this may cause a change in the trajectory and residence time in either entrained flow flames or open flames. Dense particles also have lower transport velocity of water to the particle surface during the drying phase and a smooth surface reduces the ignition quality of a fuel particle.

The physical characteristics vary according to the origin of the waste, and since SRF is a mixture of different wastes, it is not easy to predict these properties. The chemical composition of SRF also affect the performance of co-processing. For instance, the chemical composition determines the flue gas composition and gives different temperature profiles, which in return affect the ignition of the fuels. The variation of chemical composition and heterogeneity characteristics of SRF makes it challenging to determine these operational conditions.
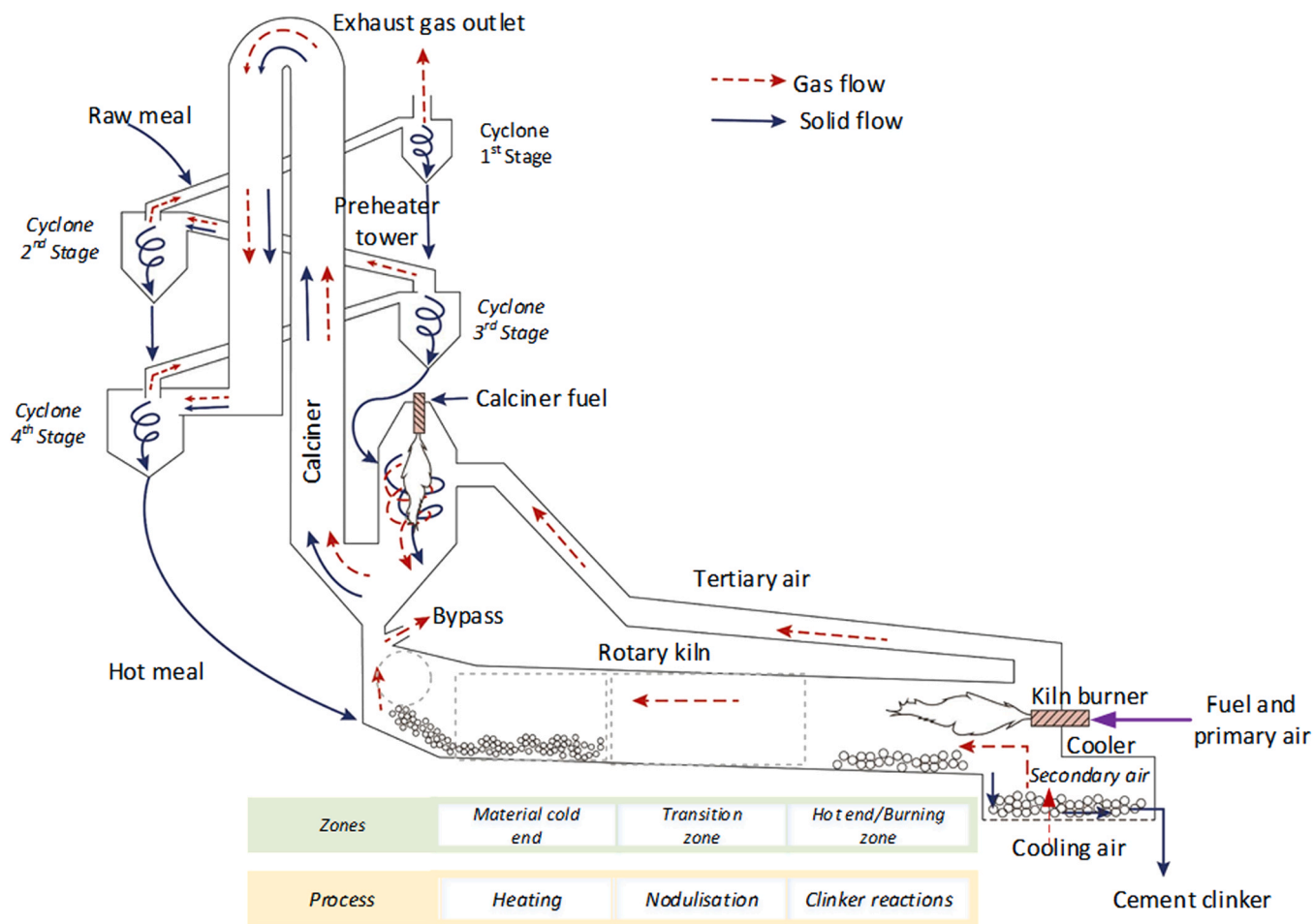
Fig. 13. Scheme of a typical kiln system.

Table 3

Characterization of waste derived fuels according to different property categories (adapted from (Velis et al., 2010)).

Property category	Properties
Chemical	Combustible matter (volatiles and fixed carbon)
	Non-combustible mater (moisture and ash)
	Proximate analysis (moisture, volatiles, fixed carbon, ash)
	Ultimate (elemental)a analysis (C, H, O, S and N)
	Other elements (eg: Cl, S)
	Trace elements (for example heavy metals)
	Major elements: Cl, P, S
	Content of fixed carbon
	Content of biogenic vs. fossil carbon
	Content of volatiles
Mechanical	Density
	Bulk solids properties (bulk density, angle of repose, flowability)
	Grindability
	Particle size distribution
	Storage properties (biological stability, sanitization) and dispersibility (fluidity)
Calorific	Lower heating value and higher heating value
	Specific minimum air requirement
	Specific minimum flue gas generation
	Adiabatic combustion temperature
	Specific heat capacity, thermal conductivity, and temperature diffusivity
Reaction kinetics	Ignition and burnout behavior
	Corrosion potential
	Devolatilization

4. Conclusion

Co-processing of secondary fuels such as SRF has an economic, social, and industrial value. SRF production and usage must also be economically, socially, and technically feasible to attract end-user applications. A cement plant is a suitable destination for SRF because of the high-temperature energy-intensive processes occurring in such systems. Co-processing in cement kilns/precalciners effectively utilizes the material and energy value of the wastes, thereby conserving natural resources by reducing the use of virgin material.

The main challenges that deaccelerate the SRF usage in cement kilns/calciners are the larger particle size, higher moisture content, higher chlorine content and fluctuations in quality and composition. These factors reduce the conversion rate of SRF fuel particles, extend the drying process, and increase the requirement of volumetric gas flow. The risk of corrosion due to increased chlorine content and wearing problems due to large inert pieces in SRF such as glass and metal are common problems. Cement manufacturers must pay special attention to maintaining stable operation and clinker quality during SRF co-processing.

Most of the drawbacks associated with SRF are directly or indirectly connected to the inherent properties of SRF, which can be eliminated or controlled by improving the quality of SRF pre-processing. The heterogeneity of SRF particles can be reduced by adopting a proper pre-processing system and maintaining a favorable storage system that does not deteriorate SRF properties with time. Improving infrastructure facilities for SRF characterization and extensive and frequent sampling before /during/after use in the cement production process is vital to understand the daily variation in SRF quality better.

This review shows that alternative fuel consumption in the cement industry is expected to expand in the next thirty years. SRF will play a significant role in the years to come.

Data availability

Data will be made available on request.

Declaration of Competing Interest

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

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