Review

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Review

Outlook of Solid Recovered Fuel (SRF) for the Substitution of Fossil Fuels in the Industrial Utilities

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Abstract: This paper reviews the requirements for the production, quality, and quality assurance of solid recovered fuels (SRF) that are increasingly used for the substitution of fossil fuels in the industrial utilities. The economical, technological and environmental aspects should be considered before using SRF as an alternative fuel. In general, the most important factors determining the commercial production of SRF referred to the calorific values and their available amounts adopted in the starting materials. Furthermore, the low-melting impurities and undesired constituents/elements, including chlorine, sulfur, potassium and sodium, may pose negative impacts on air pollutant emission and slagging & fouling in the process utilities. In this regard, the vent emitted from the industrial utilities must comply with the effluent standards of stationary sources like particulate, sulfur oxides, nitrogen oxides, heavy metals (e.g., lead, cadmium, and mercury) and dioxins. For these reasons, this work will summarize the legal or regulatory requirements under development in Asian countries (i.e., Japan, South Korea, and Taiwan) and European Union (EU). Finally, the outlook of solid recovered fuel (SRF) in the waste management and industrial sectors will be addressed to echo the sustainable development goals (SDGs).

Keywords: solid recovered fuel; industrial utility; energy recovery; air pollution concern; slagging & fouling; regulatory measure

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1. Introduction

To manage waste generation and treatment efficiently, and also reduce greenhouse gas (GHG) emissions or dependence on fossil fuels that contribute to global warming (or climate change), sustainable material management approach has been developed by ranking waste management hierarchy [1]. For non-hazardous waste management, its hierarchy focuses on the order as follows: source reduction & reuse, recycling, energy recovery, and treatment & disposal. In the waste recycling phase, however, it is not technically or economically feasible to recycle all the components (including paper, plastics, textiles, and other combustible materials) of municipal solid waste (MSW) and non-hazardous industrial waste as materials for producing derived products. Therefore, the MSW recycling plants or material recovery facilities may be designed to produce a refuse derived fuel (RDF) as the end material, which has been developed throughout North America and European Union (EU) countries during the 1980s and 1990s [2]. These RDF pellets were extensively used in paper mill furnaces, cement kilns, power plants and also in district heating plants. However, there were concerns about the heterogeneity of RDF in its waste material types, calorific value and heavy metal emissions during the co-incineration or co-combustion. To promote the applications of waste-to-fuel by defining its standards or specifications, the European Commission mandated the CEN Technical Committee CEN/TC 343 for classifying solid recovered fuels (SRF) in the early 2000s [3,4].

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In brief, SRF is a subgroup of RDF which comprises solid fuels from non-hazardous waste, only aiming at reusing it for energy recovery purposes with high efficiency [5].

With the announcement of SRF standards, its production and use indicated a growing industry in the EU countries since the early 2000 because it was used as alternative fuels in dedicated fluidized bed incinerators like cement kilns and coal-fired power plants [6]. The production and use of SRF not only converts non-recyclable waste materials into electricity and heat, but also reduces GHG emissions by offsetting the need for energy from fossil fuels [7,8]. On the other hand, this waste treatment approach also called waste-to-energy (WTE) system, which must be subject to stringent air pollution standards regarding particulate, sulfur oxides (SOx), nitrogen oxides (NOx), hydrogen chloride (HCl), heavy metals, and air toxics (including dioxins and furans) [9,10]. Table 1 summarizes the characteristics of solid recovered fuels (SRF) and their environmental and combustion effects [11,12]. To mitigate the environmental, technological and health concerns from the SRF use (co-incineration or co-firing) in high energy-intensive industries (i.e., paper-making, cement-making and steel-making), the classification codes and standards of SRF were announced or revised by several developed countries over the past decade [5,13–18].

This paper summarizes the legal or regulatory requirements of SRF based on the economical, technological and environmental aspects in European Union (EU) and Asian countries (i.e., Japan, South Korea, and Taiwan). The regulatory measures for controlling emissions and residues (remains as ash) from SRF combustion were also discussed [19–23]. Finally, the outlook and suggestions of SRF in the waste management, industrial and energy sectors were further addressed to echo the sustainable development goals (SDGs) and the mitigation of GHG emissions.

Table 1. Characteristics of solid recovered fuel (SRF) and their environmental and combustion effects.

Characteristics		Effects	Comments
Physical properties	Moisture content	Storage durability and dry-matter losses, calorific value, self-ignition	
	Calorific value (CV) [1]	SRF utilization	Including gross calorific value (GCV) and net calorific value (NCV).
	Ash content	Particulate emissions, ash utilization/disposal, combustion technology	
	Physical dimension, forms	Hoisting and conveying, combustion technology, bridging	
	Density	SRF logistics (storage, transport, handling)	Including bulk density and particle density.
Chemical properties	Carbon (C)	Calorific value	Based on Dulong's Formula
	Hydrogen (H)	Calorific value	Based on Dulong's Formula
	Oxygen (O)	Calorific value	Based on Dulong's Formula
	Nitrogen (N)	Emissions of NO_x, N_2O and NH_3. Corrosion	Acid precipitation due to formation of nitric acid
	Chlorine (Cl)	Emissions of HCl, PCDD/PCDF and trace gases (e.g., $COCl_2$). Corrosion. Lowering ash-melting temperature	KCl–$FeCl_2$ and NaCl–$FeCl_2$ systems having low temperature eutectics in the range 340–390°C.

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	Sulfur (S)	Calorific value. Emissions of SO_x. Corrosion	Based on Dulong's Formula. Acid precipitation due to formation of sulfuric acid.
	Fluorine (F)	Emissions of HF and trace gases (e.g., COF_2). Corrosion	
	Potassium (K)	Corrosion (heat exchangers, superheaters). Lowering ash-melting temperature. Aerosol formation. Ash utilization.	One of alkali metals. Used as plant nutrient
	Sodium (Na)	Corrosion (heat exchangers, superheaters). Lowering ash-melting temperature. Aerosol formation.	One of alkali metals.
	Calcium (Ca)	Increase of ash-melting temperature. Ash utilization.	Used as plant nutrient
	Magnesium (Mg)	Increase of ash-melting temperature. Ash utilization.	Used as plant nutrient
	Phosphorus (P)	Ash utilization.	Used as plant nutrient
	Heavy metals [2]	Emissions of toxic/carcinogenic metals. Ash utilization. Aerosol formation	Possibly regarded as hazardous waste
	Other relevant elements [3]	missions of particles containing silica, alumina and oxides (e.g., Fe_2O_3, TiO_2, MnO).	Depending on starting materials of SRF.

[1] Contents of organic/inorganic elements. [2] Including mercury (Hg), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), lead (Pb), zinc (Zn), and so on. [3] Including silicon (Si), aluminum (Al), titanium (Ti), manganese (Mn), and so on.

2. SRF Development in Developed Countries/Regions

Over the past three decades, waste-to-energy (WTE) option may make complementary contribution to non-hazardous combustible waste (e.g., waste plastics, waste fiber, waste paper, and other biological residues) management by adopting material recovery and disposal in landfills. In this regard, the production of waste-derived fuels (i.e., RDF, SRF) has become a quite popular waste treatment approach in different countries and regions because of the growing market demand for the energy-intensive industrial sectors under the considerations of global warming mitigation and operation cost [24]. In response to the sustainable waste management and GHG emission mitigation, the SRF production and use by some developed countries or regions were briefly reviewed [13,15,16,25], focusing on the criteria, specifications and standards for producing qualified SRF products.

2.1. European Union (EU)

Since the early 1990s, the quality standards of SRF have been drawn up by some EU countries, including German, Finland and Italy. In order to establish a comparable guideline within EU region, the European Standardization Committee (CEN) announced the Technical Committee CEN/TC 343 "Solid Recovered Fuels" in 2002. Furthermore, the quality requirements of SRF are based on the technical standard UNI EN 15359 ("Solid recovered fuels — Specifications and classes") in 2011 [25]. In 2021, the international standard ISO 21640 ("Solid recovered fuels — Specifications and classes"), listed in Table 2, has already announced to replace the EN 15359.

- Lower heating value (LHV) or lower calorific value (LCV), which is related to energy property and displayed in MJ/kg.

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- Chlorine (Cl) content, which is associated with the degree of fouling on WTE facilities and expressed in percentage by weight (wt%).
- Mercury (Hg) content, which is correlated to the significance of environmental concerns and expressed as median or 80th percentile value in mg/MJ.

Table 2. Quality standards of solid recovered fuel (SRF) in European Union (EU).

Quality item	Limit [1]					Unit
	1	2	3	4	5	
Lower heating value	≧ 25	≧ 20	≧ 15	≧ 10	≧ 3	MJ/kg (as received, Mean)
	≧ 5,981	≧ 4,785	≧ 3,589	≧ 2,392	≧ 718	Kcal/kg (as received, Mean)
Chlorine content	≦ 0.2	≦ 0.6	≦ 1.0	≦ 1.5	≦ 3	wt% (dry basis, Mean)
Mercury content	≦ 0.02	≦ 0.03	≦ 0.05	≦ 0.10	≦ 0.15	mg/MJ (as received, Median)
	≦ 0.04	≦ 0.06	≦ 0.10	≦ 0.20	≦ 0.30	mg/MJ (as received, 80% percentile)

[1] Based on ISO 21640 ("Solid recovered fuels – Specifications and classes", 2021).

2.2. Japan

In Japan, the term "Refuse derived paper and plastics densified fuel (RPF)" was adopted to be different from RDF. The new types of alternative fuels were used in Japanese mills since the early 2000s [26]. To promote the use of RPF, the Japan RPF Industry Association was thus established in 2012. According to the Japanese Industrial Standards JIS Z7311:2010, the types, classes and quality standards of refuse plastics-paper fuel (RPF) are listed in Table 3. The main materials of RPF are paper (e.g., newspaper, corrugated board) and plastics from refuse (MSW). The mixture of wood scraps, fiber waste and rubber waste are also acceptable if the quality of RPF meets quality requirements in Table 3. It should be noted that the limit values shown in Table 3 are average values of the latest six test results. Notably, there were no heavy metal standards including Hg, which was relatively simpler than in other countries

Table 3. Quality standards of refuse plastics-paper fuel (RPF) in Japan. [1.]

RPF-grade	RPF-coke	RPF			Unit
Grade		A	B	C	
Higher heating value [2]	≧ 33	≧ 25	≧ 25	≧ 25	MJ/kg
	≧ 7,883	≧ 5,972	≧ 5,972	≧ 5,972	Kcal/kg
Moisture	≦ 3	≦ 5	≦ 5	≦ 5	wt%
Ash	≦ 5	≦ 10	≦ 10	≦ 10	wt%
Residual chlorine	≦ 0.6	≦ 0.3	> 0.3, ≦ 0.6	> 0.6, ≦ 2.0	wt%

[1] JIS Z 7311 ("Refuse Derived Paper and Plastics Densified Fuel", 2010). [2] Also called gross calorific value (GCV).

2.3. South Korea

To increase the proportion of WTE (or solid refuse fuel, also abbreviated as SRF) in South Korea, the production of SRF from combustible waste via physical separation (e.g., magnetic separation) and mechanical processes (i.e., crushing, shredding, and sorting) have been well developed over the past two decades [27]. Prior to 2013, the SRF was grouped into refused plastic fuel (RPF), refuse-derived fuel (RDF), tyre-derived fuel (TDF), and wood chip fuel (WCF). Since January of 2013, the term SRF (solid recovered fuel) was introduced in South Korea by the national legislation ("Act on the Promotion of Saving and Recycling of Resources Enforcement Regulation") where two types of SRF are currently recognized as an SRF and a bio-SRF (or biomass-SRF). Table 4 shows the relevant parameters and limit values for SRF adopted in South Korea. As listed in Table 4, this country has standards for 10–12 parameters, including lower heating value (LHV), shape and size, and chlorine, mercury, moisture, sulfur, ash, cadmium, lead, and arsenic contents, as well as biomass and chromium contents for bio-SRF [15].

Table 4. Quality standards of solid recovered fuel (SRF) in South Korea.

Quality item	Limit [1]		Unit
	SRF [2]	Bio-SRF [2]	
Diameter	≦ 50	≦ 50	mm
Length	≦ 100	≦ 100	mm
Moisture	≦ 20	≦ 15	wt% (as received)
Biomass content	- [3]	≧ 95	wt% (dry basis)
Ash	≦ 20	≦ 15	wt% (dry basis)
Lower heating value	≧ 14.65	≧ 12.56	MJ/kg (as received)
	≧ 3,500	≧ 3,000	Kcal/kg (as received)
Chlorine content	≦ 2	≦ 0.5	wt% (dry basis)
Mercury content	≦ 1.0	≦ 0.6	mg/kg (dry basis)
Lead content	≦ 150	≦ 100	mg/kg (dry basis)
Cadmium content	≦ 5	≦ 5	mg/kg (dry basis)
Sulfur content	≦ 0.6	≦ 0.6	mg/kg (dry basis)
Arsenic content	≦ 13	≦ 5	mg/kg (dry basis)
Chromium	- [3]	≦ 70	mg/kg (dry basis)

[1] Based on "Act on the Promotion of Saving and Recycling of Resources Enforcement Regulation". [2] Pellet form. [3] Not available.

2.4. Taiwan

In the previous study [18], the promotion of SRF and its quality standards (Table 5) in Taiwan have been addressed to reduce the dependence on imported fossil fuels, alleviate the environmental loadings from MSW incineration facilities and also mitigate GHG emissions by higher energy efficiency. In 2023, the Taiwan government announced the draft guidelines/standards for promoting bio-SRF and adding new items into the regulation ("Standards for Air Pollutant Emission from Boiler"). In order to step up the international net-zero trends by 2050, the Taiwan government declared the "2050 Net-Zero Transition in Taiwan" in April 2021. In March 2022, the National Development Council further announced "Taiwan's Pathway to Net-Zero Emissions in 2050 - 12 Key Strategies" [28], as shown in Figure 1. Obviously, the production of SRF and its use in the energy-intensive industries are very close to the key strategies of resource recycling & zero waste and energy saving & efficiency. When using bio-SRF in the energy and industry sectors, the key strategies of carbon sink and carbon capture, utilization & storage (CCUS) may be gained by enhancing forest management and photosynthesis.

Table 5. Quality standards of solid recovered fuel (SRF) in Taiwan.

Quality item	Limit	Unit	Standard method [2]
Lower heating value [1]	≧ 10	MJ/kg (as received)	NIEA M216.00C
	≧ 2,392	Kcal/kg (as received)	
Chlorine content	≦ 3	wt% (dry basis)	NIEA M217.00C
Mercury content	≦ 5	mg/kg (dry basis)	NIEA M360.01C
Lead content	≦ 150	mg/kg (dry basis)	NIEA M360.01C
Cadmium content	≦ 5	mg/kg (dry basis)	NIEA M360.01C

[1] Also called net calorific value (NCV). [2] Set by Ministry of Environment (Taiwan).

Figure 1. Twelev key strategies for promotion 2050 carbon neutrality policy in Taiwan [28].

3. SRF Production and Use in Connection with Sustainable Development Goals (SDGs)

In June 1992, the Earth Summit, also called as the United Nations Conference on Environment and Development (UNCED), was held in Rio de Janeiro (Brazil), spotlighting a new blueprint for international action on environmental and development issues in the 21 century. Subsequently, the Commission on Sustainable Development (CSD) was created in December 1992 to ensure effective follow-up of UNCED. Thereafter, the World Summit on Sustainable Development (WSSD), held in Johannesburg (South Africa) in 2002, reaffirmed the full implementation of Agenda 21 and also declared the "United Nations Decade for Education for Sustainable Development (DESD)" (2005-2014). Based on the implementation results of DESD, the 17 Sustainable Development Goals (SDGs) were further set by UN in September 2015, which focuses on targeting the 2030 Agenda for Sustainable Development by integrating all aspects of social well-being, economic growth, and environmental protection [29]. More significantly, every issue like activity, course, policy, plan and program can be related to these SDGs in some aspects, even becoming strategic frameworks for sustainable development of a country, region, or area. For instance, the food loss & waste (FLW) management and valorization are relevant to SDG-2 (organic fertilizer by food waste valorization), SDG-7 (biogas-to-power by anaerobic digestion of food waste) and SDG-12 (responsible consumption & production by FLW promotion) [30].

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As mentioned above, the use of SRF in the combustion system will bring about significant environmental advantages in terms of fossil fuel saving (thus reducing GHG emissions) and urban infrastructure supporting due to the shortage of non-hazardous waste (including MSW) treatment facilities [31–33]. Figure 2 depicts the SRF production and use with relevance to the SDGs, which are briefly stated as follows:

- SDG-2 (Zero hunger): Relevant to the organic fertilizer by reusing non-hazardous bottom ash derived from RF (especially in bio-SRF) combustion due to its richness in plant nutrients like potassium, calcium, magnesium and phosphorus.
- SDG-7 (affordable and clean energy): Relevant to the energy recovery from SRF (especially in bio-SRF) by the forms of electricity or steam (heat) in the industrial boilers or co-generation utilities.
- SDG-9 (Industries, innovation & infrastructure): Relevant to the use of SRF in the energy-intensive industries.
- SDG-9 (Sustainable cities & communities): Relevant to the production of SRF for mitigating the shortage of MSW treatment facilities (incineration plants and sanitary landfills).
- SDG-12 (Responsible consumption & production): Relevant to the recyclable materials from MSW (e.g., waste paper, waste plastics, woody discards) for producing SRF.
- SDG-13 (Climate action): Relevant to the reduction in GHG emissions due to the use of SRF in replacement of fossil fuels.

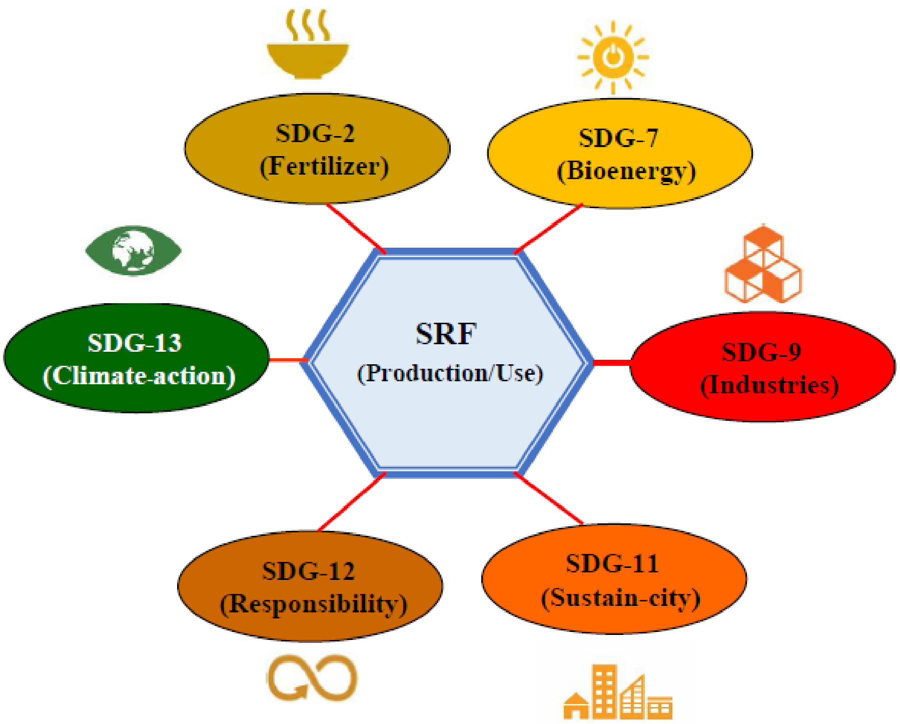

Figure 2. Production and use of SRF in relevance with sustainable development goals (SDGs).

4. Regulatory Measures for Controlling Emissions and Residues from SRF Combustion

4.1. Emissions of Air Pollutants from SRF Combuistion

The industrial combustion systems by using SRF co-firing or co-incineration must meet very stringent air emission standards due to the relevant elements and constituents contained (as summarized in Table 1). In this regard, some starting materials for producing SRF are not reprocessed into the production line. They include waste tire, plastics containing polyvinyl chloride (PVC), and woody residues containing heavy metals like chromated copper arsenate (CCA). Therefore, these waste-to-energy facilities should install the air pollution control based on the maximum available control technology (BACT) like baghouse (bag filter), scrubber, selective non-catalytic reduction

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(SNCR) and carbon injection. In addition, they have elaborate monitoring systems for accomplishing the acceptable levels of criteria air pollutants and air toxics. Table 6 listed the air pollutants from SRF combustion and their environmental and health Impacts [9,11,15,34].

Table 6. Air pollutants from solid recovered fuel (SRF) combustion and their environmental and health Impacts.

Air pollutants	Sources	Environmental Impacts	Health Impacts
Carbon dioxide (CO_2)	Major combustion product	Direct greenhouse effect. However, its emissions from bio-SRF are regarded as C-neutral.	An asphyxiant gas, not classified as toxic or harmful.
Carbon monoxide (CO)	Incomplete combustion	Indirect greenhouse gas through O_3 formation	A poisonous gas, especially in influencing people with asthma, and suffocation.
Methane (CH_4)	Incomplete combustion	Direct greenhouse effect. Indirect greenhouse gas through O_3 formation.	High CH_4 concentrations can displace oxygen in the air, thus causing hypoxia.
Non-methane volatile organic compounds (NMVOC)	Incomplete combustion	Indirect greenhouse gas through O_3 formation.	Negative effect on the human respiratory system, central nervous system and organs (e.g., kidney).
Polycyclic aromatic hydrocarbons (PAHs)	Incomplete combustion	Beneficial to smog formation.	Carcinogenic effects (especially exposed to benzo(a) pyrene).
Particles	Combustion products as forms of soot, char and tar and also from SRF containing inorganics	Reversed greenhouse effect through aerosol formation. Indirect effects of heavy-metal levels in deposited particles.	Negative effect on the human respiratory system. Carcinogenic effects due to toxic metals attached.
Nitrogen oxides (NOx)	Minor combustion products from SRF containing nitrogen and in the air under certain conditions	Acid precipitation (rain) [1]. Reversed greenhouse gas effect through aerosol formation. Indirect greenhouse gas through O_3 formation. Smog formation.	Negative effect on the human respiratory system. NO_2 is a mildly poisonous gas like CO.
Nitrous oxide (N_2O)	Minor combustion products from SRF containing nitrogen	Direct greenhouse effect	Indirect effect through O_3 (ozone layer) depletion in the stratosphere.
Ammonia (NH_3)	Small amounts generated from combustion of SRF containing	Acid precipitation (rain).	Negative effect on the human respiratory system.
Sulfur oxides (SOx)	Minor combustion product from SRF containing sulfur	Acid precipitation (rain) [1]. Reversed greenhouse gas effect through aerosol formation.	Negative effect on the human respiratory system, including asthmatic effect.

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Heavy metals	Minor combustion products from SRF containing them due to evaporation and attach onto particles	May pose catalytic effects on the formations of secondary air pollutants.	Due to the food chain, some (e.g., Hg, Pb, Cd) are toxic. Some (e.g., As, Cr, Ni) have carcinogenic effects.
Ozone (O_3) [2]	Second combustion product from atmospheric reactions of CO, CH_4, NMVOC and NOx	Direct greenhouse effect. Vegetation damage. Smog formation. Material damage.	Negative effect on the human respiratory system, including asthmatic effect.
Hydrogen chloride (HCl)	Minor combustion product from SRF containing chlorine	Acid precipitation (rain).	Negative effect on the human respiratory system.
Dioxins and furans (PCDD/PCDF)	Trace combustion products from SRF containing C, Cl and O in the presence of catalysts	Indirect effects of PCDD/PCDF levels in deposited particles.	Due to respiratory route and food chain, they are highly toxic and carcinogenic.

[1] Including vegetation damage, and corrosion and material damage. [2] Ground level.

4.2. Treatment and Disposal of Residual Ash Waste from SRF Combustion

The bottom ash residue from the WTE facilities using SRF may represent 15-30 wt% of the incoming fuels, depending on the ash contents and combustion conditions. The ash is typically passed through a magnetic separator to remove ferrous materials and over grates to screen bulky pieces. Due to the SRF derived from non-hazardous waste and/or MSW, the recycling possibilities for the bottom ash include natural aggregate substitutes, cement-based applications and vitrified products because the main constituents consist of silica (SiO_2), alumina (Al_2O_3), calcium oxide (CaO) and ferric oxide (Fe_2O_3) [11,35,36]. On the other hand, the slagging and fouling tendency in the industrial utilities shall be considered when using SRF [19–23]. In the previous study [18], several slagging & fouling indices have been summarized to evaluate the operational problems during the coal/SRF co-firing in the combustion systems. Among these alkali metal and alkaline earth metal elements, the contents of oxides of potassium (K), sodium (Na), calcium (Ca) and magnesium (Mg) have been incorporated into these slagging ratings. Table 7 summarizes the data on the melting temperature of K/Na/Ca/Mg oxide/fluoride/chloride/sulfate/nitrate possibly formed during SRF combustion. As seen in Table 7, it was found that some of these inorganic compounds have lower melting points which may be lower than the operation temperature in the combustion systems, thus causing significant slagging and agglomeration problems associated with SRF co-firing or co-combustion. Regarding the fouling tendency, some starting materials containing the high contents of chlorine and/or sulfur should be excluded from the SRF production, including PVC and waste tire.

Table 7. Melting temperature of mineral salts possibly formed during SRF combustion.

Element	Mineral salt	Melting temperature (°C)
Potassium (K)	Potassium nitrate, KNO_3	334
	Potassium oxide, K_2O	740
	Potassium chloride, KCl	770
	Potassium sulfate, K_2SO_4	1,069
Sodium (Na)	Sodium nitrate, $NaNO_3$	308
	Sodium chloride, NaCl	801
	Sodium sulfate, Na_2SO_4	884
	Sodium oxide, Na_2O	1,132

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Calcium (Ca)	Calcium nitrate, $Ca(NO_3)_2$	561
	Calcium fluoride, CaF_2	1,418
	Calcium sulfate, $CaSO_4$	1,460
	Calcium chloride, $CaCl_2$	772
Magnesium (Mg)	Magnesium fluoride, MgF_2	1,263
	Magnesium chloride, $MgCl_2$	714
	Magnesium nitrate	129 (dihydrate) 89 (hexahydrate)

5. Conclusions and Outlook

Traditionally, the term "refuse derived fuels" (RDF) has been used in the waste-to-energy (WTE) facilities. However, the term "solid recovered fuels" (SRF) differs from RDF because it is a regulated fuel that must meet the quality requirements (i.e. classification and specification) by the national regulations or standards in some developed countries like EU, Japan, South Korea. SRF can be produced locally from individual or mixed streams of municipal (MSW), commercial (CW), non-hazardous industrial (IW) and construction & demolition (CDW) wastes. These input streams will influence their elemental compositions, thus characterizing the air pollutants and ash residues from SRF combustion in the end-users (e.g. cement kilns, power plants, gasification plants, and paper & pulp mills). In conclusions, the use of SRF not only reduces the consumption of fossil fuels and their GHG emissions in the energy-intensive industries, but also alleviates the environmental loadings from MSW incineration plants and sanitary landfills in the urban infrastructure. In this regard, the SRF production and use may be an available path to a circular economy in combination with some aspects of sustainable development goals (SDGs).

In order to promote the production and use of SRF in response to the industrial market demand for reducing fossil fuel use and also mitigating GHG emissions, some trends or approaches were addressed below:

- Expanding the available combustible and lignocellulosic waste streams, including bamboo residues, fruit tree trimmings, crop residues (e.g., rice husk, crop straws), regenerated oils (i.e., purification/separation of spent lubricating oil and spent motorcycle oil from the commercial and services sectors).
- Avoiding the low environment-friendly starting materials for producing SRF like woody materials/timbers containing copper chrome arsenic (CCA) and Pb-based paints, waste plastics containing Cd/Pb-based plasticizers.
- Revising the quality standards of SRF by listing the elements related to heavy metals (including copper, zinc, and nickel) and slagging & fouling tendency (including potassium, sodium, and sulfur).
- Using X-ray fluorescence spectrometry (XRF) as a preliminary screening tool in the determinations of heavy metals (e.g., Hg, Cd, Pb) and chlorine based on the quality standards of SRF.
- Increasing the use of cleaner SRF (e.g., bio-SRF) in the energy-intensive industrial sectors like paper-making, petrochemical industry, steel-manufacturing and cement-making.
- Co-firing bio-SRF in the coal-fired power plants for reducing the use of fossil fuels and the emissions of GHGs.
- Setting the stricter standards (or limits) of the air pollutants emitted from the stationary source of the industrial utilities with using SRF.
- Adopting other thermochemical processes (e.g., gasification, pyrolysis) for upgrading the added value of SRF via the production of valuable materials/fuels like syngas and pyrolytic oils.

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