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Review

Toward Viable Industrial Solid Residual Waste Recycling: A Review of Its Innovative Applications and Future Perspectives

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Abstract: Industrial solid residual waste (ISRW) generated during and/or due to the making of energy, heat, and raw materials poses a major threat to a sustainable future due to its large production quantities and complex characteristics. Especially improper disposal of ISRW (e.g., coal ashes, municipal waste residue, and biomass ashes) not only threatens human health but can also cause environmental hazards such as water, soil, and air pollution, upsetting the global balance. Given the environmental impacts as well as increasingly stringent disposal regulations, lack of landfills, and economic constraints, more sustainable and naturally friendly management strategies are being adopted for ISRW. While numerous studies in the literature have considered various characteristics of ISRW, a complete appraisal of the entire practice, from making to disposal, is still lacking. This paper presents an overview of the making, features, and traditional and innovative managing tactics of ISRW within the context of a general legal framework. This paper provides a scientific review of the various production types, global production quantities, and characteristics of ISRW. Additionally, the orthodox management strategies of ISRWs are scrutinized from a sociological and ecological standpoint, and diverse techniques for more viable and secure management are elucidated. This review culminates in an examination of the global impact and advantages of ISRW management policies based on legislation and regulations. Consequently, this paper seeks to elucidate the extant practices and a few recent advancements pertaining to ISRWs. Additionally, it underscores the ecological, sociological, and economic issues engendered by ISRWs and proposes innovative applications and production technologies.

Keywords: industrial ash; coal; biomass; municipal; fly ash; bottom ash

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1. Introduction

In the modern era, continuous development of industry due to urbanization and rapid population growth raises the demand for energy and raw materials [1]. Especially after the manufacturing revolt, fossil fuels are gradually employed to meet this claim [2]. The majority of the energy used in sectors, mainly in the making of raw materials, is obtained from fossil fuels [3]. From the sustainability and ecological impact points of view, use of energy production methods is essential compared to traditional fossil fuel energy sources [4]. Hence, using more viable sources such as biomass and municipal solid waste (MSW) in addition to traditional resources in energy production has recently become widespread and extensive [5,6]. However, although renewable and green fuels are more cost-effective and readily available compared to conventional fuels, their potential demand remains limited [7]. Considering the development of technology and limited resources, the trend towards renewable and green energy methods is anticipated to rise soon.

To satisfy a growing energy claim, using renewable energy sources in addition to traditional methods has led to the construction of many conventional power plants in addition to the existing ones [8,9]. This results in the generation of millions of tons of ISRW (coal ash, MSW ash, and biomass ash) on a daily basis in various facilities, contingent upon the fuel type employed, and the raw materials produced. For instance, as indicated by the 2020 data, coal ash's global making is estimated as 7575 M tons (MT). The majority of coal ash is produced in China (3.76 MT) and India (760 MT) [10]. ISRW's global making in urban areas is estimated to be ~3.5 MT/day. This value is projected to reach an estimated 6.1 MT in 2025 [5]. Biomass ash's making is estimated to be 500 MT/year globally [11].

ISRW is becoming a vital issue in terms of its viable and safe management, given its huge making quantities and complex nature [12]. Thus, many administrations worldwide have enacted many legislations and regulations to prevent ecological and sociological problems caused by ISRW [13]. For example, US EPA has recognized a series of rules aimed at promoting sustainable management of many hazardous wastes, with a particular focus on coal ash. EPA inspects the plants/facilities making these wastes under strict guidelines and mandates certain engineering requirements [14]. Legislation and regulations such as EPA seek to ensure the safer storage and transportation of ISRW, as well as limiting its disposal [15]. This will abate the ecological problems caused by ISRWs and manage waste in a way that poses the least threat to human health [16]. However, the disposal of these wastes is now the most untenable and ecologically threatening of all management strategies. ISRW is mostly disposed of in landfills, dumps, and settling ponds [17]. Although different methods are used for the disposal of ISRWs, severe ecological harms arise owing to issues such as radiation and leaching. Disposal of ISRWs in various storage sites causes land occupation and limits using green assets [18]. Increasing the amount of ISRW produced day by day will lead to a decrease in landfills and, consequently, a significant rise in economic problems [19]. Thus, it is essential to dispose of ISRWs in a more viable manner, reusing these wastes and transforming them into value-added products.

ISRWs are widely employed in various construction applications, chiefly in concrete and cement production [20]. Due to the large structure and robust physical characteristics of ISRWs, they have begun to be employed as raw materials in a variety of fields, including zeolite, ceramics, road structures, adsorbents, glass, and soil enhancement [21]. Despite the extensive utilization of ISRWs across diverse sectors, the actual potential and depletion of these wastes remain constrained [22,23]. Thus, modern research endeavors to bolster the utilization of ISRWs in novel domains and to transform them into products with substantial economic and commercial value [24]. For instance, ISRWs can be employed in diverse fields, including geopolymers as an innovative and ecologically benign alternative to cement, aerogel as an insulating material, retrieving rare earth elements, and carbon nanotubes as a thermal and chemical energy source [25–29]. Considering these innovative and green uses of ISRWs, it is inevitable that they will significantly reduce environmental and economic problems, especially in the future [21]. In addition to the aforementioned methods, it is evident that new products will emerge that will enhance the economic value of ISRWs due to technological advancements. However, there is no comprehensive study that scans the innovative use areas and/or making methods of ISRWs today. Thus, it is crucial to perform a full study on areas of use and making technologies of ISRWs, with a focus on elucidating their environmental and economic potential.

This mini-review offers processes involved in the generation, management, and disposal of ISRWs. This paper begins with an analysis of ISRW production and management, covering their representative properties and characteristics. Subsequently, conventional recycling and reuse techniques, as well as pioneering and high-value applications of ISRWs, are discussed. Finally, a concise evaluation of the sustainable management of ISRWs within the legal framework is presented. In essence, this study aims to illuminate existing practices related to ISWs and a few advances made today. Thus, an overview of the applications and production technologies of ISRWs is provided, revealing their environmental, economic, and sociological potential. Additionally, innovative and green uses of waste are highlighted by detailing the processes from the generation to disposal of ISRWs. The necessity of using ISRWs as a source of raw materials in different sectors and their recycling potentials have been emphasized in detail. It is stated that innovative and green ISRW applications will significantly reduce environmental and economic problems in the future.

2. Generation, Types, and Production Amounts of ISRW

Industrial growth, the rise in the urbanization rate, and the desire to improve the quality of life in recent years have increased global energy consumption almost threefold since 2000 and continue to do so (Figure 1). This increase is projected to grasp 740 M terajoules through 2040 [30]. To meet this increasing demand, various raw materials are burned in energy stations and these raw materials give rise to different industrial waste ashes. This title provides brief information about the production method, amount, and types of industrial wastes such as coal ash, MSW residue, and biomass ash.

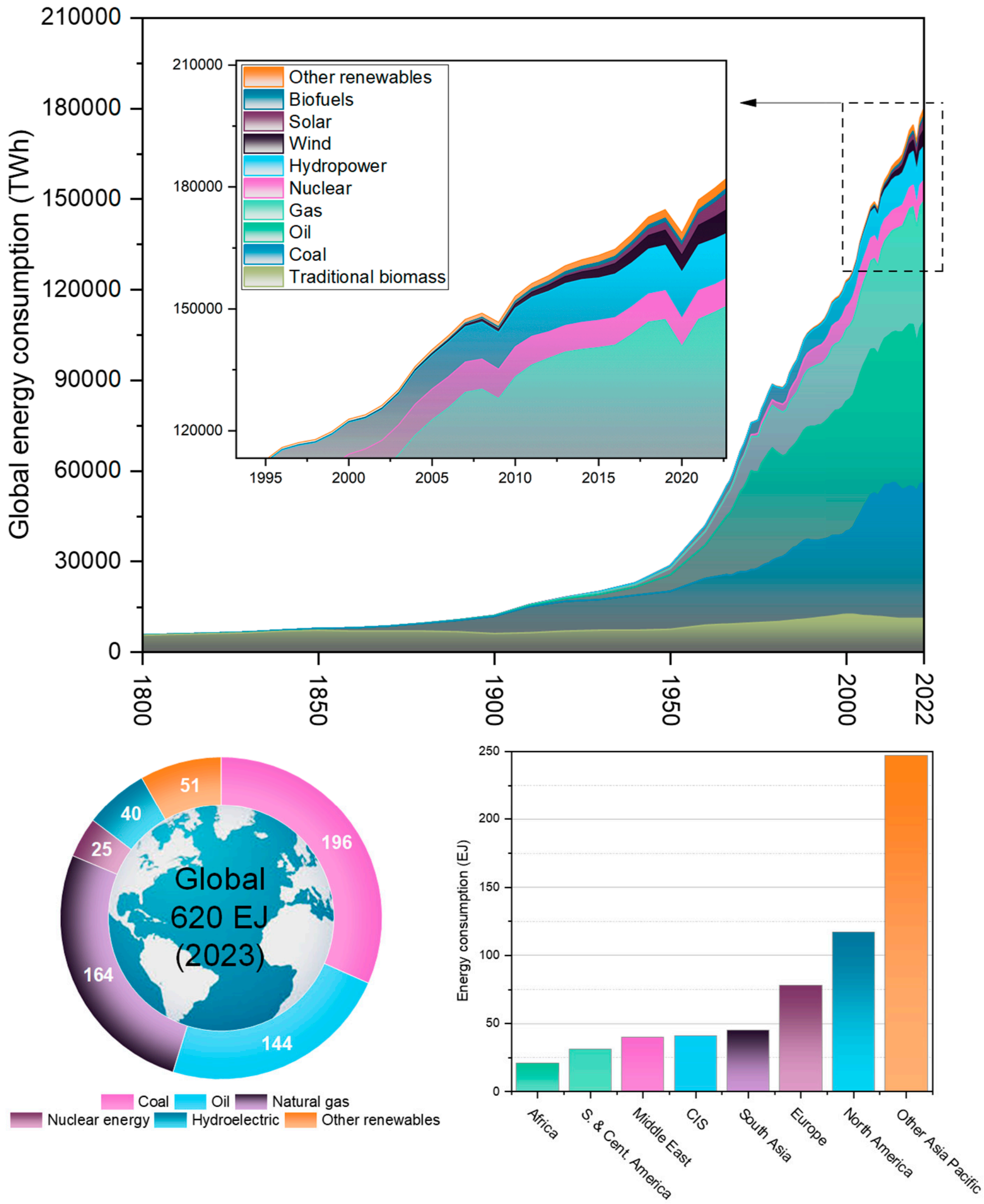

Figure 1. Global energy consumption volumes [31,32].

2.1. Coal Ashes

Coal is a sedimentary rock composed primarily of elements such as carbon, hydrogen, and oxygen. Coal comprised 31% of the world's principal energy consumption and played a significant role in generating 41.1% of global electricity in 2014 [33]. Coal offers a cornerstone of energy provision for many states, and it played a crucial role by constituting 65.5% of electricity, making and contributing significantly to saleable heat production in 2015, with OECD countries relying on it for 82.7% and China for 56% [34]. Recent data indicate a notable 6% increase in coal consumption, amounting to 160 exajoules in 2021 [35]. Expectations suggest a likely rise in coal usage surpassing 50%, essential to meet global electricity demand goals by 2030 [36].

In parallel with coal's intensive usage to encounter energy desires, there are rises in amounts of coal bottom ash (C-BA) and coal fly ash (C-FA) within combustion plants, ranging from 20%–30% to 70%–80%, respectively [37]. C-BA consists of unburned minerals that are shaped by coal burning and gather on boiler walls and bottoms. C-BAs are coarse-grained, permeable, dark-colored, and sand-like materials. C-FAs are small and spherical fine-particles, which are separated out of gases by electrostatic precipitators.

According to statistics, the production of C-BA ranges from 150 to 200 million tons, while C-FA production ranges from 600 to 800 M tons [18]. Malaysia, recognized as the leading power plant operator in Southeast Asia, produces the highest volumes of both C-BA and C-FA annually [38]. Current data show that fossil fuels, predominantly coal (58%) and gas (25%), will account for 83% of Malaysia's electricity generation by 2024, up from 43% in 2014. This anticipated increase in coal consumption for electricity generation implies a corresponding rise in coal ash production (C-FA and C-BA). This electricity generation results in a significant volume of coal fly ash (C-FA), amounting to approximately 6.8 M tons, and C-BA, totaling around 1.7 million tons in Malaysia [39]. Likewise, based on 2021 data, India annually produces around 232 million tonnes of C-FA and 30 M tons of C-BA. In 2017, the US produced more than 9.7 million tonnes of C-BA, while China's production reached approximately 90 million tonnes in 2019 [40]. Figure 2 shows the global coal and fly ash production quantities.

Coal ashes (C-BA and C-FA) are defined as solid wastes that are classified as hazardous waste and need to be managed according to regulations [41]. Currently, the management of coal ash is traditionally carried out in landfills, dumps, and settling ponds [42]. As mentioned above, given the huge production volumes of coal ash, current management strategies are inadequate in many parts of the world. Also, disposal of coal ash by traditional methods risks many living species, especially human health. The risk of skin–eye irritation and respiratory tract infections increases significantly in living organisms exposed to coal ash [43]. Coal ashes contain radiochemical contaminants (e.g., ^{222}Ru and ^{220}Ru) and toxic metals (e.g., chromium, nickel, copper, and lead), which directly damage many resources such as agriculture and fisheries due to their contamination of soil and water resources (groundwater and surface water) [44]. Coal ash is also stored in huge landfills, limiting the use of productive agricultural land and causing land occupation [27]. Given the problems associated with the inadequate management and disposal of coal ash, it is crucial to better understand the characteristics of these wastes and adopt innovative and sustainable management strategies to preserve ecological balance.

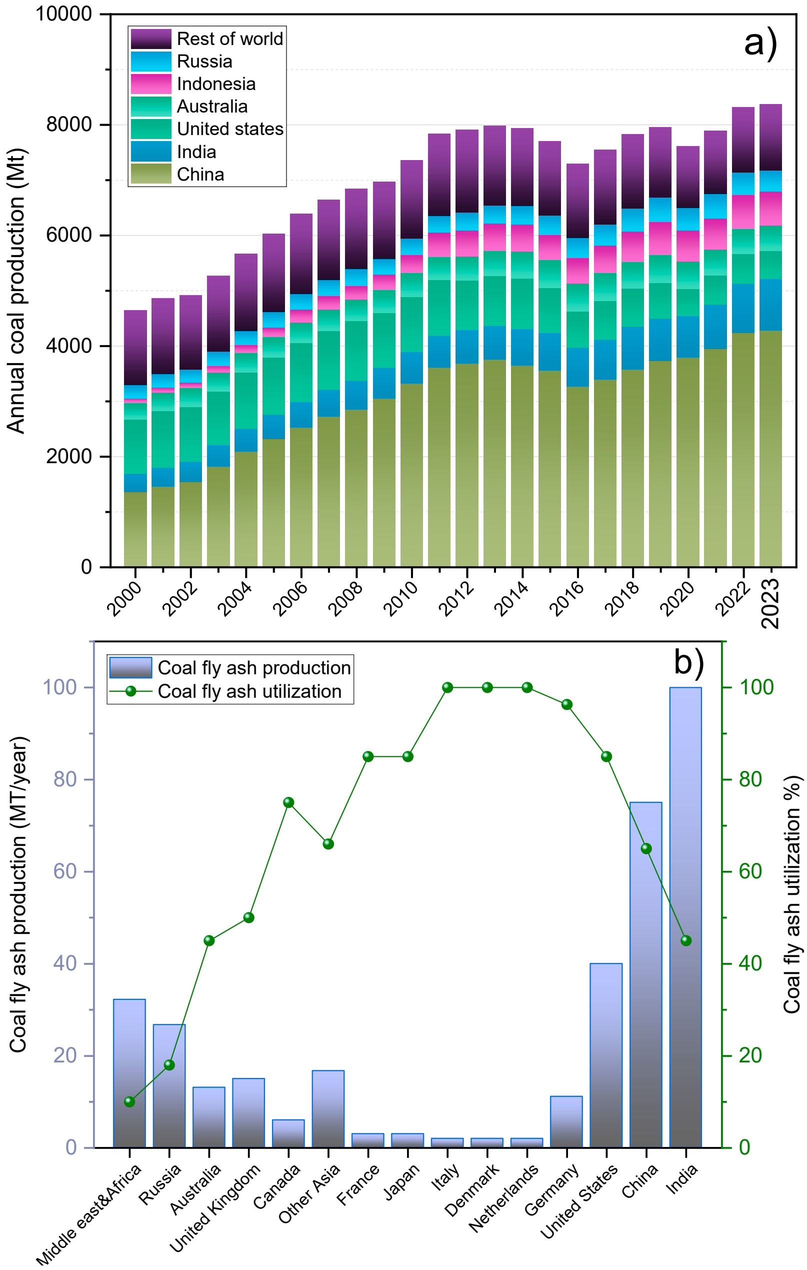

Figure 2. General coal (**a**) and fly ash (**b**) production amounts in the world [23,35].

2.2. Municipal Solid Residual Waste (MSRW)

Municipal solid waste (MSW) is generated by individuals/businesses and generally consists of garbage, packaging materials, food waste, textiles, plastic waste, rubber, wastepaper, leather, tools, and similar substances. It is also possible to detail MSW as household waste (e.g., food waste, packaging materials, clothing, and similar); commercial waste; waste from industry and production; waste from construction, repair, and demolition (e.g., concrete, lumber, and metal); and hazardous waste requiring special treatment (e.g., batteries and pharmaceuticals). In the coming decades, owing to the urbanization effect, industrialization, and population growth, the MSW production rate will increase tremendously [45]. MSW's global production is planned to hold 3.8 B tons by 2050 [46]. Despite the per capita amount of MSW being below 300 M tons in 2017, MSW's total volume grasped ~1.8 B tons by 2020. Analyzing the rate of progress from 2004 to 2029 advises a momentous rise in MSW per capita through 2050 [47].

Incineration is used in the treatment of MSWs and obtaining energy from them, and excessive amounts of MSW can be reduced by this method. The wastes formed by means of burning processes may be categorized as ash. MSRW-bottom ash (MSRW-BA) constitutes 80% of the remaining waste, with MSRW-fly ash (MSRW-FA) making up the other 20% [48]. In the US, 9 M tons of MSRW, mostly bottom ashes, was made in 2017 [49]. Europe produces around 20 M tons of bottom ash annually from MSW burning [50]. The annual MSRW-BA generated in China is above 13 M tons [51]. Figure 3 shows MSW production by country and world population.

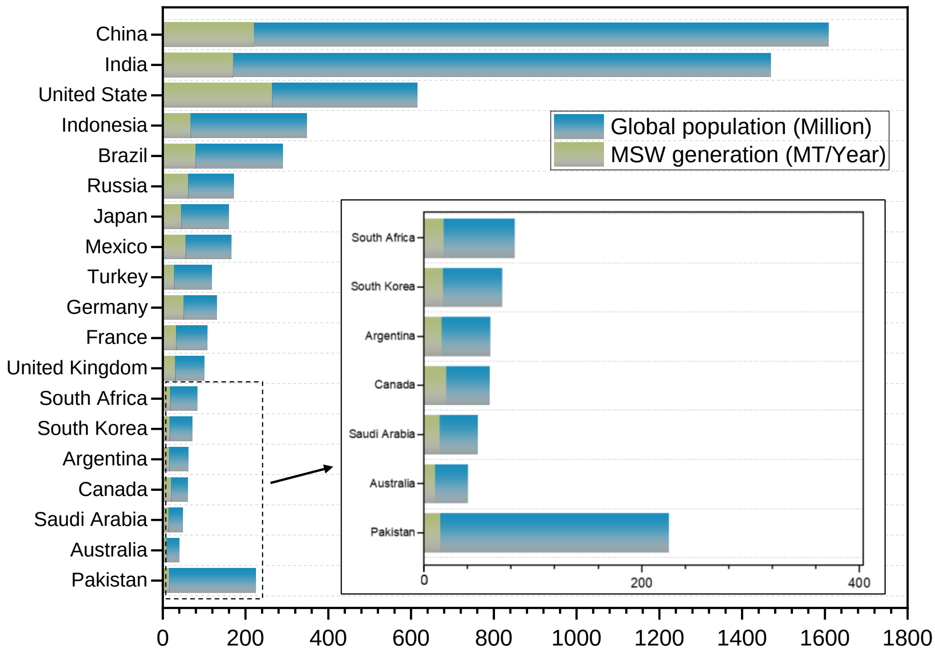

Figure 3. MSW generation by country and global population [5].

The enormous production volumes of MSWs worldwide cause significant complexities in disposal systems. Many management strategies are becoming of major environmental concern. The choice of appropriate management and disposal methods is crucial to subsidize the national coffers and for a sustainable future. Different alternative strategies such as landfilling, incineration, composting, and recycling are used for MSW management [52]. Incineration and landfilling are widely used in more developed countries due to their high costs [53]. Additionally, landfilling is one of the most widely used methods due to its low cost. Among the least popular methods is composting [54]. However, all these disposal methods cause soil, water, and air pollution and damage the ecosystem [55]. Especially incinerated MSWs (MSRW-BA and MSRW-FA) cause many disasters such as land use, melting of glaciers, climate change, ozone depletion due to excessive greenhouse gas emissions, toxicity, and damage to natural resources [56]. Landfilling of incinerated waste is recognized worldwide as a hazardous disposal method [57]. Consequently, the sustainable disposal of MSWs and the suitability of their management systems are of vital importance. For this reason, the potential of MSWs should be evaluated as a resource according to their characteristics, and their recycling potential should be revealed.

2.3. Biomass Ashes

Biomass is the general name for biological materials obtained from plants and animals and is used as an energy source. Globally, annual biomass waste production is estimated at approximately 140 gigatons. Key constituents of these wastes include wood and farming goods, and solid and garbage waste. To utilize waste biomass, it is necessary to convert waste biomass into useful products. Using waste biomass for electrical energy or fuel is broadly stated [58]. Waste biomass energy, also known as bioenergy, currently accounts for the largest share of renewable energy consumption and 9% of the world's total energy supplies [59]. It is estimated that the current energy supply can be tripled by using biomass resources sustainably in the next 20 years, which includes an increase from approximately 55 EJ to 150 EJ [60]. Considering the future potential of biomass use, it is estimated that by 2035, 5% of agricultural land (240 M hectares) could be employed to raise biomass for biofuel/energy production [61].

Various pretreatments are available to improve biomass properties and make processing processes more efficient, including drying, pelletizing, briquetting, and pyrolysis [62]. After pretreatment, the biomass is conveyed to a biomass-fired power plant for combustion and burned at high heats in specially designed furnaces or boilers. Biomass bottom ash (B-BA) and biomass fly ash (B-FA) resulting from burning are collected; BA accrues at a burning chamber's bottom, while FA is captured by filtration systems. In total, 170 M tons of ash are made each year [12]. Figure 4 shows the biomass ash making and total energy depletion.

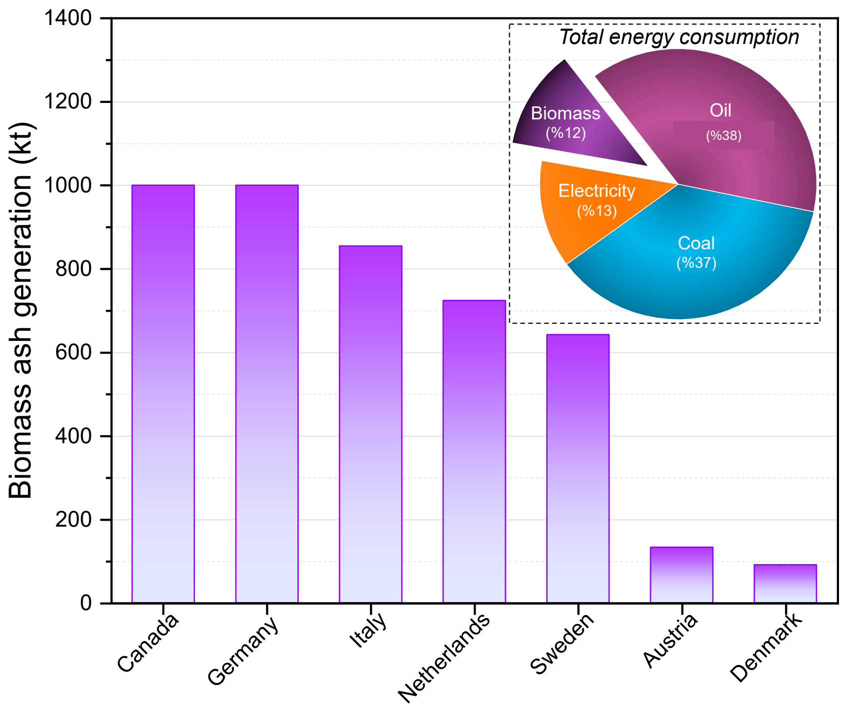

Figure 4. Biomass ash production versus total energy consumption [63].

Biomass wastes are traditionally disposed of by composting, fertilizing, feeding, and landfilling [15]. However, uncontrolled management of these wastes causes environmental pollution by significantly increasing greenhouse gas emissions, water pollution (groundwater and surface), and pathogen spread [64]. In order to reduce such problems, biomass wastes are incinerated for fuel and/or energy production in developed countries compared to traditional methods. Incineration is considered as a completely clean and sustainable method compared to other methods [65]. However, the huge quantities of biomass ashes (Figure 4) resulting from incineration are of ecological concern. Overarching concerns about biomass ashes include many issues such as disposal, storage, utilization, and transportation [66]. Generally, biomass ashes are stored in landfills, which are a source of environmental pollution and a threat to living health. These landfills are constantly filling up due to the disproportionate increase in the production of ashes, significantly increasing costs [17]. New trends emphasize the use of ashes in more sustainable and green ways due to their characteristics. In this way, the utilization potential of biomass ashes as a raw material source in different areas such as construction, agriculture, and recycling fuel can be unlocked [67]. Moreover, it is likely that in the future more innovative and multi-technology-integrated alternative methods will be used to reduce the amount of ash production.

3. Properties of Industrial Solid Ashes

Under this heading, the characteristic (physico-chemical and mineralogical) features of ashes obtained from the burning of coal, MSW, and biomass waste will be briefly discussed.

3.1. Characteristics of C-FA and C-BA

C-BA and C-FA are wastes of coal combustion. Characteristic properties of these ashes depend on variables such as a kind of coal and its additives, burning temperature, and boiler type.

C-BA's mainly consist of SiO_2, Al_2O_3, and Fe_2O_3 components [68]. Since these components vary by coal type/burning situations, chemical properties vary from country to country [69]. For example, the percentage of Al_2O_3 is 15% in the USA, while it is around 20% in Spain [70,71]. On the other hand, the amount of calcium it contains varies between 0.5% and 17%, and the amount of MgO varies around 2%, while the amount of SO_3 varies between 0.007% and 2.66% [72,73]. C-BA is a light/brittle product, its grain surface is coarse, and its shape is lanky [74]. The sizes of these particles range from about 0.075 mm to 10 mm. It seems a bit gloomier than C-FA [75]. The shape of C-BA is angular and irregular, and its internal structure is porous [76].

C-FA's key constituents are SiO_2, Al_2O_3, and Fe_2O_3, just like C-BA. Akin to bottom ash, fly ash's physico-chemical properties depend on coal form/combustion techniques [77]. For industrial uses, especially in the cement industry, FA is generally separated into two categories: C and F. According to ASTM C618, if the amount of SiO_2, Al_2O_3, and CaO is >70% by weight, ashes are branded as Class F. If it ranges from 50% to 70%, it is branded as Class C [78]. Class C has over 15% CaO and is self-cementing, while Class F is under 5% CaO, and needs an activator to form cement. Class C also has higher alkali and sulfate levels [79]. C-FA is fine-grained and the color of the grains is black/gray. The grain size diameter varies by country and is poorly graded. Fly ash is non-plastic, so it maintains its shape and does not expand when utilized as a foundation material [80]. Some physico-chemical properties of C-BA and C-FA are listed in Table 1.

Table 1. Physico-chemical features of C-FA/C-BA [81,82].

	C-FA	*C-BA*
Physical Features		
Color	Reddish-tan/black	Dark grey/black
Specific gravity (no unit)	1.9–2.6	1.39–2.6
Specific surface, S_s	5–10 (m^2/g)	93–600 (m^2/kg)
Apparent density (g/cm^3)	2.1–3.0	-
Max. dry density (g/cc)	0.9–1.6	-
Optimum water content (%)	18.0–38.0	11.61–32.23
Grain size (µm)	1–100	>100
Porosity (%)	30–65	-
pH	1.2–12.5 (most are alkaline)	-
Fineness modulus	-	1.8–5.6
Water content, ω (%)	-	1.0–28.9
Chemical Features	*(%)*	*(%)*
SiO_2	39.08	51.51
Al_2O_3	10.58	18.7
Fe_2O_3	2.71	9.5
CaO	30.80	5.08
MgO	11.61	0.93
SO_3	2.11	0.14
Na_2O	0.42	0.52
K_2O	0.17	2.56

3.2. Characteristics of MSRW-FA and MSRW-BA

MSW burning generates two key ashes: bottom and fly. The majority of solid waste generated from MSW comprises 80 wt% of MSRW-bottom ash (MSRW-BA). MSRW-BA is a type of ash consisting of a mixture of metals, glass, stones, and unburned organic waste material. This ash generally presents a solid granular form with predominantly coarse particles like sand and gravel, alongside finer particles such as silt and clay [83]. The heating and subsequent cooling processes during waste incineration contribute to the irregular texture and increased porosity of MSRW-BA, enhancing its water absorption capacity [84]. Compared to MSRW-BA, MSRW-fly ash (MSRW-FA) creates 5–20% of the full incinerated waste. These ashes have small particle sizes and high hydrophilic properties [85]. Both types of ash have similar basic components (Al, Ca, Si, Na, K, S, Fe). While the mineralogical structure of bottom ash is shaped according to the conditions of the environment (open air) in which it is stored, the mineralogical structure of FA is shaped by various events (melting, evaporation) that occur during combustion. When evaluated in terms of environmental impact, MSRW-BA may cause leaching as it contains heavy metals, while MSRW-FA may adversely affect human health as a result of a rapid spread of small grains in air when the flue gas filtration system is not suitable or works inadequately. Some physical and chemical properties of MSRW-BA and MSRW-FA are listed in Table 2.

Table 2. Physico-chemical features of MSRW-FA/MSRW-BA [86–89].

Physical Features	*MSRW-FA*	*MSRW-BA*
Color	Gray to light brown	Dark gray to black
Density (g/cm^3)	0.7–1.5	1.0–2.5
Particle Size	<100 µm	0.1–50 mm
LOI	1%–10%	1%–5%
Specific Gravity	2.2–2.8	2.0–2.5
Chemical Features	*(%)*	*(%)*
SiO_2	3.25	19.12
Al_2O_3	2.31	12.04
Fe_2O_3	0.39	9.31
CaO	38.70	43.12
SO_3	4.59	2.40
Na_2O	11.57	2.36
K_2O	8.35	0.85

3.3. Features of B-FA and B-BA

Biomass fly ash (B-FA) and biomass bottom ash (B-BA) are residual materials created by the burning of biomass in thermal facilities. These ashes contain oxidized minerals along with unburned organic materials such as carbohydrates and lignin [64]. The yield and quantity of produced ash differ from the type of biomass, burning temperature, and type of burning chamber. B-BA accumulated beneath the burning hall grate is typically the weightiest portion by maximum grain diameters ranging from 2 to 9 mm. In contrast, B-FA is the finer component suspended in plant stack gases with a maximum particle size of approximately 200 µm [90]. Density and grain diameter of B-BA and B-FA differ from the type of material burned [91]. The mineralogical/chemical features of biomass ashes, similar to their physical features, differ from material type, burning technique, and furnace structure. Wastes contain high doses of Si, Al, Ca, P, and Na, and water-soluble toxic elements like Pb, Cr, As, and Zn [92]. Some physical and chemical properties of B-BA and B-FA are presented in Table 3.

Table 3. Physico-chemical features of B-FA/B-BA [93–97].

Physical Features	*B-FA*		*B-BA*	
Color	Gray or light brown		Dark gray or black	
Density (g/cm^3)	0.6–1.2		1.5–2.0	
Particle size	1–100 µm		0.1–50 mm	
Porosity	High		Low	
Hygroscopicity	Tendency to absorb moisture		Less tendency to absorb moisture	
Chemical Features	*Rice husk (%)*	*Corn cobs (%)*	*Olive plant (%)*	*Forest biomass (%)*
SiO_2	94.38	27.65	6.84	72.20
Al_2O_3	0.21	2.49	2.73	3.32
Fe_2O_3	0.22	1.55	1.39	0.78
CaO	0.97	13.19	31.41	17.16
SO_3	0.92	7.14	-	-
K_2O	-	-	12.31	0.75

Various management strategies are being applied to utilize the unique characteristics of industrial solid waste residues (coal ashes, municipal solid waste ashes, biomass ashes), to overcome the problems associated with their disposal and to transform them into industrial resources. Particularly considering the unique characteristics of ISRWs (discussed more extensively in Section 3), numerous studies are currently focusing on reuse and/or recycling in different applications (e.g., soil–environmental remediation, cement–concrete products, and brick–ceramic–glass manufacturing) [93,98,99]. For instance, elements such as Ca, Mg, Fe, P, K, S, and Zn in ISRWs are compatible with the macro–micronutrients in the soil and therefore have a significant potential for soil improvement [100–102]. Also, different studies emphasize that the ability of ISRWs to retain heavy metals is very successful in terms of environmental remediation [25,103].

The physical, chemical, and mineralogical properties of ISRWs lead to its use as a dominant material in the construction industry (e.g., concrete and building materials). Due to their pozzolanic nature, ISRWs are often used instead of portlandite, the main component of cement. Thus, ISRWs contribute to the improvement in many properties of concrete such as permeability, workability, and low heat of hydration. Moreover, the rich oxide content of ISRWs (e.g., SiO_2, Al_2O_3, Fe_2O_3, and CaO) enables their utilization as raw materials for building materials such as bricks, glass, and ceramics [22,104,105]. Apart from the traditional uses for ISRWs mentioned above, the use of advanced techniques (e.g., geopolymer, carbon nanotube, and silica aerogel) is becoming increasingly widespread today to limit the amount of waste generation and ensure a more sustainable perspective [106–108]. Due to the difficulty and cost of implementation of these methods, however, their utilization rate and know-how remain limited. Within this framework, to highlight the different areas of utilization of ISRWs, a detailed review on reuse and recycling is presented in Section 4 and advanced and current techniques in Section 5.

4. Management of ISRW from Industrial Waste-to-Energy Conversion Processes

Today, rapid population expansion and urbanization worldwide lead to a sharp rise in energy needs. These demographic changes and urbanization processes show that energy consumption is enhancing day by day in both developed and developing countries. With the manufacturing revolt, coal, oil, and natural gas have become key resources of energy fabrication, and the use of these fuels has become rapidly widespread [109]. However, environmental effects of fossil fuels, especially climate change, air pollution, and depletion in natural resources, have brought the requirement for a changeover to more viable methods of energy fabrication to an agenda. In recent years, in line with environmental concerns and sustainability goals, the tendency to turn to renewable energy bases in place of fossil fuels has strengthened [110]. Solar, wind, hydroelectric, geothermal, and biomass options are used to reduce environmental impacts and increase energy security. Among energy sources, using biomass and municipal waste in energy fabrication has become increasingly widespread [111]. Biomass energy provides an alternative that supports environmental sustainability by providing energy fabrication from organic waste. Similarly, municipal waste is converted into energy with various technologies and this process both reduces the amount of waste and provides energy fabrication. However, new environmental and management harms also arise with using these energy bases. Burning of fuels employed in plants causes the making of industrial waste and ash. These wastes consist of various types like coal ash, biomass ash, and MSW ash, and millions of tons of waste are made every year. Imbalance between industrial ash making and the present sum of use necessitates the development of the scope of use and wastes' artefact base with novel techniques [69].

The management of industrial ashes is of great environmental and economic importance. Improper management of these ashes can lead to soil–water effluence, and hostile impacts on health [112]. The management of industrial ash is a critical factor determining the environmental performance of power plants. Improper disposal of ashes can cause toxic components to leak into waterways and soil. These toxic components may include heavy metals, radioactive substances, and other harmful components. In addition, the accumulation of industrial ash in landfills can leak into groundwater resources, causing water pollution and endangering drinking water resources [113]. The management and maintenance of ash ponds can also require large costs; these costs are constantly increasing due to the limited capacity of the landfills and the increasing annual ash volume. The areas where industrial ash is accumulated are usually collected in facilities such as large-scale regular landfills, ash ponds, and sedimentation ponds. These methods can cause various problems due to environmental risks and long-term maintenance requirements. They may include adverse environmental effects such as toxicity, radioactivity, and leakage risks. In addition, ash dumping in landfills can lead to a decrease in recyclable resources and the deterioration of agricultural land [114]. Over time, increases in ash capacities can lead to a decrease in landfill areas and a significant increase in disposal costs. In this context, there is a great need to recycle industrial ashes without harming the environment or to transform them into a value-added product.

ISRWs burned in thermal power plants to obtain energy and heat pose a great threat to the global order every passing day. Disobeying the correct disposal of ashes resulting from combustion may disrupt natural balance and create environmental risks [115]. Seeing increasingly strict removal protocols, depleting landfills, and high discarding costs, more efficient and ecologically friendly tools are needed for management of industrial ashes. Instead of the storing and disposing of industrial ashes, adopting reuse options may offer major chances regarding fiscal progress and reducing natural risks. Let us say that coal ash is utilized as a concrete stabilizer in the building sector, while biomass ash can be evaluated as an agricultural fertilizer. Since the properties of ashes largely depend on the material burned, the material properties of ashes should be thoroughly determined before using them in any application. In addition, analyzing the physical/chemical properties of industrial ashes can determine the areas of use of these wastes and develop appropriate recycling methods.

Innovative technologies aim to process industrial waste more effectively and minimize potential damage. In the future, it will be possible to reduce green impacts and support industrial development by developing more viable and efficient solutions in industrial waste management. The conversion of industrial ashes into valuable products is an inevitable necessity for the realization of both environmental protection and economic development goals. Disposal of industrial ashes is one of the chief green and economic problems encountered in energy production. In parallel with rapidly increased energy demand and the transition process towards renewable energy sources, industrial wastes need to be managed effectively. For this purpose, it is of great importance to process industrial ashes with ecologically appropriate methods, ensure their reuse, and transform them into valuable products. Products produced from industrial ashes have various advantages and disadvantages and have promising development potential in the future. The main advantages of these are that they reduce the consumption of natural resources and minimize the amount of waste going to landfills [116]. This contributes to reducing carbon emissions, preserving raw materials, and promoting circular economy principles. In addition, using industrial ashes as raw materials can reduce production costs compared to traditional materials. In addition to all these advantages, there are also disadvantages such as the composition of industrial ashes varying depending on resources and production processes, which has negative effects on the consistency and quality of the final products [117]. In addition, some industrial ashes may require significant energy-intensive processes such as grinding and thermal treatment to make them usable, which may reduce some of the environmental benefits. In addition, some industrial ashes may contain hazardous substances such as heavy metals and therefore need to be carefully processed and managed to prevent environmental pollution and health risks. Although products made from industrial ash present some challenges, they have the potential to contribute to a more sustainable and resource-efficient future. Future developments are expected to focus on improving processing technologies to make industrial ash more efficient and environmentally friendly [118]. For a green energy production process, it is of great significance to process industrial ashes with environmentally friendly methods, re-evaluate them, and convert them into value-added products. In this context, industrial ashes have many uses in various sectors. These ashes are used in many different areas such as cement, concrete, brick, block, glass, and ceramic production; road base and filling material; soil stabilization; fertilizer waste stabilization; and water treatment. In this section, the production of cement, concrete, brick, glass, and ceramics from industrial ashes and soil stabilization areas will be discussed (Figure 5).

Figure 5. Traditional uses of industrial solid residual waste (ISRW).

4.1. Cement and Concrete Production

Cement is a broadly utilized basic structure product in construction areas, especially in plaster/concrete. Portland cement, a popular kind of this fine product that hardens when in contact with water, consists of lime and clay minerals. However, large amounts of CO_2 emissions occur during the cement production process; approximately 0.85 tons of CO_2 is released to produce cement (1 ton) [119]. This green impact is a factor that challenges the cement industry in terms of sustainability. For example, using industrial wastes like FA, slag, or silica fume in concrete making is a key step that is preferred to reduce CO_2 emissions from cement production and minimize environmental impact [120].

Coal ashes are extensively recycled in the building sector since they have pozzolanic properties depending on the CaO mass they contain [121]. Thanks to their chemical/mineralogical properties, they have a function in the cement and concrete industry. C-FA offers pozzolanic and structural properties thanks to its ability to replace clinker, the basic component of OPC. The cementing properties of C-FA increase workability/drainage in concrete, while being used as a cement substitute, it decreases manufacture prices by reducing hydration heat of the concrete mix and prevents risk of initial cracking [122]. With this use, it offers high toughness and final force in concrete. In addition to increasing mechanical performance, it provides environmental benefits by reducing toxic emissions and energy consumption with less cement use.

Additionally, it contributes to less pollution of the environment with use of thermal plant waste. Using C-FA in concrete varies between 15% and 35% and C-FA-based geopolymers offer a significant innovation in the field of construction materials by providing durability and strength comparable to cement [123]. The suitability of C-FA for several structural applications is continuously proven and its role in the industry is increasing. Like C-FA, C-BA has been used in the construction sector for many years. Recently, use of C-BA as cement or a fine aggregate, especially in concrete production, has been increasing. Using C-BA as a thin layer in concrete can reduce the density of concrete while increasing compressive strength and pozzolanic reactions [124]. However, C-BA provides a low reactivity owing to its large particle diameter, and its surface area and reactivity should be ground at appropriate rates to be used instead of cement. As the fineness of C-BA rises, performance/quality of mortars can increase. The grinding process can also reduce the harmful effects of Al-Si reactions on concrete. However, this raises concrete production costs. It is observed that ecological effects are reduced in the construction sector, especially in cement/concrete making, with safe processing of C-BA. Recent studies have shown that cementitious mixtures formed with C-BA exhibit similar or improved ecological and mechanical properties to C-FA [69]. Using C-BA in concrete may cause less CO_2 emissions compared to natural aggregates or other alternative materials. However, further research is needed on the environmental impacts and cost benefits of C-BA. It is possible to come across different studies [124–126] in the literature where coal ashes are used in cement and concrete production.

MSRW may be benefited as a raw resource in cement manufacture due to chemical constituents they include like CaO, SiO_2, Al_2O_3, and Fe_2O_3 [127]. However, the existence of ash in cement production can negatively influence product value, remarkably owing to heavy metals and high chloride content. The potential for these harmful substances to leak into groundwater can pose a serious threat to the ecosystem, thus creating environmental concerns. Before using MSRW ashes in cement production, various pretreatment processes must be applied to ensure environmental safety. MSRW-BA and MSRW-FA may be utilized as an additional component of cement, as well as an aggregate in cementitious products, either alone or as an ash mixture [128]. In the US and Netherlands, MSRW-BA ash is commonly used in the production of concrete blocks by combining them with other concrete components [129]. Employing MSRW-BA as a trivial aggregate in the construction sector is generally in compliance with standards, but it may govern strength of concrete. FA may be more useful in concrete production due to its density, permeability, and chemical properties. Fly ash can be pelletized and used as a lightweight aggregate, but determining the correct amount to be used is critical for artefact quality, and can be handled meticulously. Using MSRW ashes in lightweight aggregate production differs from kiln type. BA is used as an additive for fine–coarse fractions in concrete, and it can be observed that the resulting concrete generally exhibits low density/compressive strength [130].

There are many studies where biomass ashes are employed in cement making [131]. These properties also vary depending on the biomass source. Using biomass ash wastes, occupying landfills, can cause environmental pollution, and in the cement industry can reduce production costs and CO_2 emissions. In addition to supporting cement production, these ashes can also play a role in concrete making. Rice husk ash of suitable size can notably enhance the strength of concrete by reducing water absorption [132].

On the contrary, palm oil ash lessens pores of concrete and raises sulfate resistance. Works exist evaluating effects of ash obtained by grinding coconut shells on concrete's strength properties [133]. The fact that biomass bottom ashes contain different-sized components and unburned materials can create some difficulties in their use. However, those with the right material properties can be employed as an aggregate or for cement creation [134]. Based on its physico-chemical properties, biomass fly ash is employed as a cement in mortar, while biomass bottom ash is used instead of sand in mixes. Studies have examined how biomass waste can be used in concrete instead of the fine fraction [135].

4.2. Brick and Ceramic Production

Bricks produced by coal ash are created by blending FA or BA, fine aggregate, cement, or lime in suitable proportions [136]. Classes F and C including C-FA are especially preferred in ash brick production [137]. The pozzolanic features of C Class C-FAs raise brick quality. Cement/lime is inserted in the produced bricks. Coal ash-produced bricks have many valuable benefits compared to others. They allow less mortar/plaster to be used through use. They could be made using less energy and machinery equipment by hydraulic pressure in field conditions. Properties of bricks produced with C-FA and C-BA differ from the sort of ash used, quantity of raw material, and making stages [138]. The amount of lime used in the mixture varies, especially according to its ratio with cement. Although there are many technologies to produce bricks with C-FA and C-BA today, not all of them may be applicable or economical. In addition, the fact that bricks made by clay/coal ash are 15%–20% lighter than traditional bricks improve their thermal filling properties [139].

Ceramic tiles are usually thin plates employed in ornate coverings of floors, ceilings, and walls. Basic components of these tiles are composed of minerals such as clay (50%), feldspar (35%), and quartz (15%). However, wastes like coal ash play a key role in the production of these tiles. C-FA and C-BA are known for their low cost and their richness in oxides like Fe_2O_3, CaO, Al_2O_3, and SiO_2. These properties provide economic and technical advantages in ceramic tile creating [140]. In the production process of ceramic tiles, chemical/natural minerals are employed in addition to coal ashes. These additional materials help develop physico-mechanical properties of tiles and provide desirable aesthetics and durability. C-FA and C-BA are also known as sintered materials and are used in glass–ceramic or glass production [141]. These materials enable their raw forms to become usable in the production of ceramic tiles or glass by heat exchange and certain chemical processes. The addition of coal waste ashes to ceramic mixtures affects important properties of tiles such as porosity, durability, density, and absorbency [142]. The drop in the density of ceramic tiles with the contribution of these waste materials can increase the thermal insulation potential of buildings, which can have a positive effect in terms of energy efficiency.

Ceramics are a material obtained by hardening non-metallic inorganic materials by firing. While silicate-based raw materials are widely used in ceramic making, MSRWs, namely the ashes resulting from the combustion of municipal solid wastes, are considered a potential resource for the ceramic industry. MSRW's high silicate content allows these ashes to be used easily and economically in ceramic manufacture [143]. It can be converted into a glass-like creation by vitrification at high temperatures [144]. During this process, ash's glassy structure is formed, while elements such as organic pollutants and heavy metals it contains can be separated by various methods. With the increasing demand and use in recent years, glass ceramics are gained by MSRW-FA [145]. Using FA in glass ceramics donates the stabilization of metals it contains in addition to lowering waste's volume. Using MSRW ashes in glass–ceramic production offers both an environmentally sustainable approach and provides economic benefits as a valuable industrial resource.

Biomass ash provides physico-chemical properties of brick products and is employed for natural resources. Brick features vary depending on raw material's structure and making process. Therefore, brick's structure differs depending on properties of biomass ashes used to prevent depleting clay deposits. For example, as stated by Kazmi et al. [146], rice husk ash could raise brick's strength, while sugarcane bagasse ash can reduce the density and enable brick production. Carrasco et al. [147] detected a decrease in conductivity in bricks produced with wood B-BA; similar decreases were observed in clay bricks made with rice husk. Ceramics produced from biomass ashes demonstrate low density/thermal conductivity, and a light product [148]. Furthermore, ceramics deal a larger range of colors compared to traditional ceramics. These ceramics serve the purpose of reducing green pollution by keeping biomass ashes in ceramics to meet the need for raw products. Using biomass ashes in brick and ceramic making has an important place among sustainable material options.

4.3. Road Construction

Coal ashes are considered as wastes appropriate for reusing in constructions. C-FA is employed as concrete, filler, sub-base, and highway base aggregate, although C-BA is preferred as filler in highway concrete, edges, steadied foundations, and asphalt aggregate [149]. Since using fillers can create high costs and environmental effects, studies with coal ashes are encouraged. The properties of coal fly and bottom ashes such as weightlessness and great solidity make these materials stand out as fillings. The use of C-FA and C-BA in road concrete significantly increases the performance of concrete. Coal ashes significantly improve road concrete's durability, strength, and workability, reducing concrete's permeability and costs [150]. Fills made using coal ash on roads are usually composed of mixtures of coal ash, cement, and liquids. Sometimes additional materials like sand/quarry dust are included in these mixtures. One of the most important features of these materials is that they can be applied without requiring compaction and vibration compared to old-style means. In addition, they can be implemented in zones that are not touched with traditional methods, increase soil carrying capacity, prevent collapses, and require less labor. These advantages make coal ash filling attractive as a basic solid in an embankment structure. The low cost of coal ash, its easy applicability, and the fact that it eliminates the need for natural filling allow it to be effectively applied to fillings with low carrying capacity. C-FA is preferred as a filler but C-BA is employed as an aggregate [151]. When coal ash is added to asphalt, strength, rutting, and abrasion resistance of the mixture are significantly improved.

MSRW ashes are a preferred product in road production due to their material properties. Especially MSRW-BA ash is more appropriate for road construction due to its high silicon and calcium content and physical properties [152]. Irregular shapes of ashes can allow their use especially in surface and road pavements. Many countries such as Spain and France prefer MSRW-BA in road pavements and have the necessary legal procedures for these applications [153]. In various studies where MSRW-BA was employed in asphalt, it was experimentally observed that asphalt's elastic modulus and tensile strength increased, rutting resistance decreased, and permanent deformation resistance improved [154]. MSRW-FA has a relatively lesser particle size, a great specific surface area, and basic features. Metals in MSRW-FA used in an asphalt mixture improve asphalt's impermeability/adhesion.

In road engineering, the durability of asphalt pavement under various conditions is of great importance. Asphalt is a mixture of several chemical components having viscoelastic properties. In this context, biomass ash is an important material example, and it is possible to come across various studies on this subject. Tahami et al. [155] studied rice husk/palm kernel ashes as fillers in mixtures and determined that mixes exhibited an upper stability and hardness modulus. Xue et al. [156] used wood sawdust ash in asphalt's modification and observed that this ash reduced the rutting feature and increased cement viscosity at great heat. These studies emphasize the importance of biomass ash to increase the durability of asphalt mixtures.

4.4. Soil Upgrading

Nowadays, dolomite/lime-added products are widely employed for soil upgrading. But they are not considered ecologically friendly and demand extensive processing to improve soil properties. Using waste ashes instead of lime can significantly reduce CO_2 emissions from lime production, slow down global warming, and improve soil structure. In addition, these ashes can balance the pH level of the soil, increase water retention capacity, provide a suitable substrate for plants, and support growth of germs [157]. C-FA and C-BA are preferred to stabilize soils [158]. This ash is alkaline, which helps maintain the pH balance of the soil. This alkaline property may vary depending on coal's source and operating circumstances of thermal power plants. C-FAs of type C are often preferred because they tend to increase soil's pH, while C-FAs of type F perform less well in improving the alkalinity of the soil. Compared to C-FAs, C-BA's higher porosity/permeability make it a more effective option in terms of soil amendment. C-FA and C-BA have additional advantages such as filtration, soil compaction reduction, and aeration. Silica in coal ash also acts as a pesticide, restricting metals' availability/movement [159].

MSRW is frequently used in soil upgrading processes due to their diverse chemical substances [160]. However, the quantity of ash in soil enhancement can be carefully attuned because this amount can influence soil's toxicity and thus plants. Failure to adjust the amount of ash properly causes elements in plant tissues to exceed suitable bounds and this can even negatively alter the natural life of animals [5]. Using biomass ash as compost in forestry can help eliminate deficiencies in basic nutrients in the soil. Ash formed by burning biomass at high heats is mineralized and the cations in it are transformed into oxides. Ca, Mg, and K minerals in this carbonate form pass into the soil. Biomass ash is considered as a basic product for soil due to its high pH value [161].

5. Advanced Techniques for the Management of Industrial Ashes

This section presents examples of high-value-added methods and products for the management of industrial solid ashes, focusing on innovative approaches that increase the trade worth and capability of these ashes. Compared to storage or disposal options, the adoption of reuse of these ashes can offer major opportunities. Industrial ashes should be turned into higher-value-added products and used in new application areas. Some innovative usage examples of industrial waste ashes are shown in Figure 6.

The areas of use in Figure 6 have encouraged the emergence of novel, environmentally friendly, and sustainable approaches that will surpass the conventional applications of industrial ashes. Therefore, it is necessary to examine the technologies linked to the parts of use of industrial ashes comprehensively and to discuss their benefit–use potential in depth. Details on some innovative use cases of industrial solid ashes (geopolymer, rare earth elements, carbon nanotubes, catalysis, and silica aerogel) are presented below.

Geopolymer cements stand out as innovative products that have the potential to replace conventional cement and reduce total heat and energy consumption in concrete production [162]. Compared to geopolymer concrete, traditional concrete has negative impacts on the environment such as the greenhouse effect and global warming due to the high use of cement (Figure 7). For example, on average, 0.85 tons of CO_2 is emitted during the production of 1 ton of ordinary Portland cement (OPC) clinker and about 8% of global CO_2 emissions are attributed to OPC production [119,163]. Therefore, a geopolymer assumes an important role in limiting the use of cement because of increasing demand for environmentally friendly technologies and strict regulations worldwide. Also, cement accounts for a large part of the high energy consumption and costs in conventional concrete production. This situation imposes a significant economic burden on businesses and significantly increases cement-related costs [164]. Previous studies have reported that costs associated with the production of geopolymer concrete are significantly lower compared to conventional concrete [165,166].

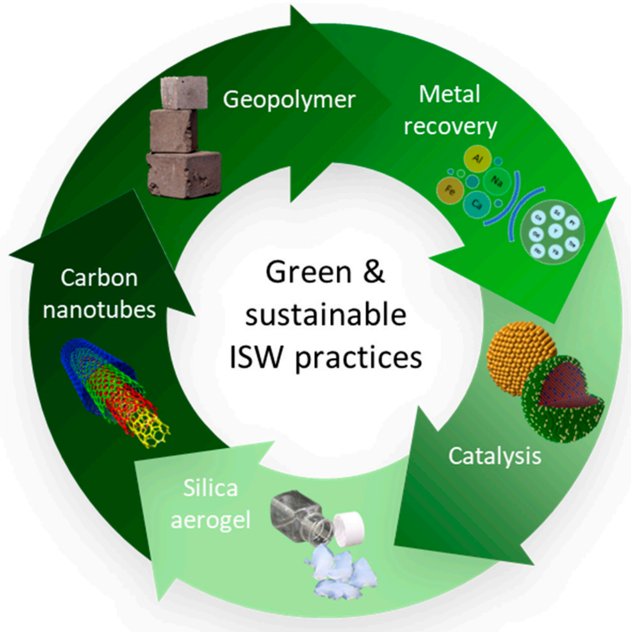

Figure 6. High-value-added and promising industrial solid residual waste (ISRW) applications.

Geopolymers produced using C-FA and C-BA are generally obtained with an aluminosilicate powder and hydroxide–silicate solution [167]. A strength increase in concrete varies depending on volume, size, activator degree, and curing conditions of C-FA and C-BA grains [168]. C-FA is a valuable precursor for geopolymers because of the crucial roles played by its key elements, SiO_2 and Al_2O_3 [169]. Although the SiO_2/Al_2O_3 ratio is on the upper end in geopolymers having C-BA, it is generally seen that geopolymers containing C-FA perform better. The factor that limits the use of C-BA and C-FA for geopolymerization is the low reactivity of both. The reactivity of C-FA is influenced by its particle size distribution and the proportion and composition of the glassy phase, whereas the reactivity of C-BA is influenced by its grinding at particular temperatures and the curing conditions applied [170,171]. There are many studies on these parameters and one of them is the research on grinding C-FAs with different types of grinding methods and observing the properties of the material [172]. The potential of geopolymers produced using MSRW ash and standing out as an environmentally friendly aluminum-silicate cementing material have been investigated in various studies [173]. It is thought that MSRW ash-based geopolymers can be an effective cement option in the building sector and can reduce the environmental effects of waste pollutants. However, the structure and physico-chemical properties of ashes can affect the performance of a geopolymer [174]. There are several findings on the potential of MSRW ash-based geopolymers to reduce toxic leakage and their use as sustainable construction materials instead of cement [175]. Biomass solid ash is considered as an innovative method in geopolymer production to reduce industrial waste and increase agricultural productivity [176]. This ash corrects the micropores of geopolymers and improves the gel phase because of the filling impact of nano-silica grains [177]. Furthermore, palm oil fuel ash, which contains a large amount of SiO_2, can be used as an additional cement-based material in geopolymer production [178]. This ash can increase the strength of geopolymers and efficiently decrease the shrinkage rate during drying by encouraging the hydration process [179].

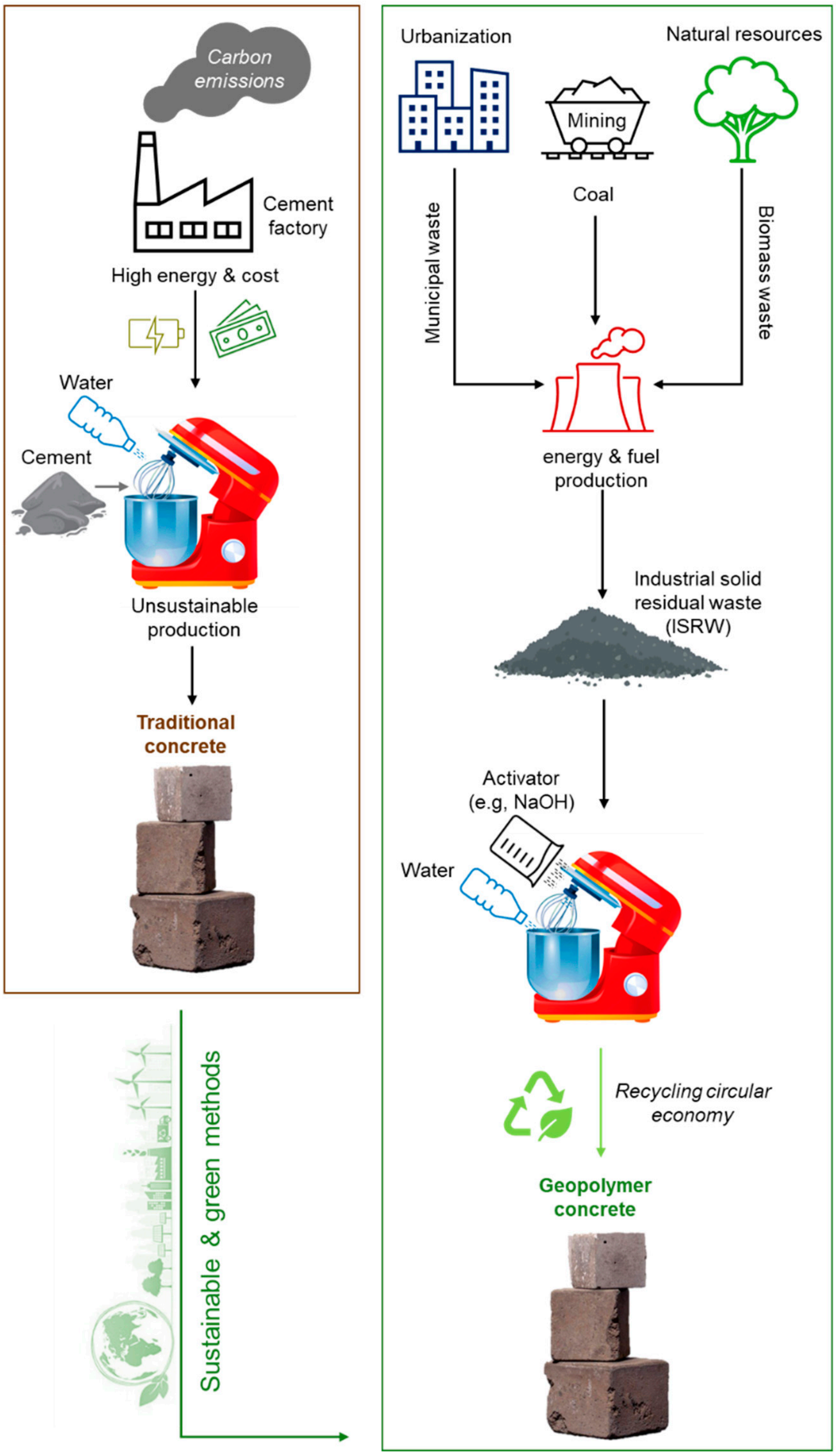

Figure 7. Traditional and innovative concrete applications.

REEs (rare earth elements), which are an important product in the utilization of industrial ashes, are critical raw materials with an important need for modern and green technologies [180]. REE extraction significantly benefits the promotion of environmental and sustainable approaches by reducing the quantity of problematic wastes such as ISRWs. Also, this process can contribute significantly to a circular economy by meeting current demand for raw materials in industry [181]. Apart from benefits, REE extraction with today's methodologies is quite expensive and the production process is complicated. Additionally, the REE extraction process is further complicated by the typical characteristics that vary from one material to another [182]. For this reason, the existing literature is very limited in REE extraction procedures and materials to be utilized [183]. Despite a wide range of potential applications of REE, a limited body of knowledge makes it essential that REE applications are more comprehensively studied economically, evaluated, and advanced in the life cycle. C-FA and C-BA contain many rare earth elements (REEs) that are unprocessed and have great commercial prices. REE concentrations in coal ash generally vary between 270 and 1480 ppm [26]. When evaluated from an economic perspective, the presence of some metals like Al and Mg and critical elements like Ge, U, Ga, Se, and V indicate high commercial potential. Moreover, the presence of these elements makes C-FA and C-BA key and valuable alternatives when considering natural resources [184]. Studies have shown that MSRW ash contains significant amounts of critical raw materials [128]. However, the low concentrations of REE in MSRW ash necessitate improvements in current methods to increase the regaining of these elements. New and profitable methods not only increase the management of hazardous substances in the waste but also increase the economic benefits [185,186]. Biomass bottom ash offers significant practical and ecological contributions due to its sustainable use despite its low trace element content. Research on rare earth elements in bottom ash has focused on the thermo/chemical behavior of these elements in various biomass transformations [187]. The most obvious advantages of REE regaining are that it reduces the storage and leaching risk of these ashes. The low concentration levels of biomass fly ash (10–100 ppm) are generally cited as the reason why these materials cannot be adequately evaluated as an REE resource. However, some investigations have also shown that they have high REE concentrations [188].

Carbon nanotubes (CNTs), another application area of waste ashes, are a new type of material consisting of graphene sheets at the nanometer scale and offering unique properties such as mechanical, optical, and electronic [189]. With their high efficiency, ability to be synthesized in large quantities, and easy fabrication procedures, CNTs are widely used in both small and large application industries [190]. Nanomaterials such as CNTs offer endless opportunities, especially in the construction industry, due to their many benefits (e.g., repurposing and integration into different materials) [191]. Efforts to utilize different types of waste (e.g., ISRW) have led to significant reductions in the production costs of CNTs. However, some CNT applications are currently very costly compared to traditional methods and impose significant operational overheads [192]. The utilization of wastes such as ISRW in CNTs not only promotes the circular economy but also plays an important role in reducing environmental problems. Different studies have emphasized that the use of CNT composites in large construction applications will increase the amount of utilization of different wastes such as coal ashes and reduce ecological problems [193]. Towards the end of the 1900s, the discovery of CNTs occurred with the discovery of molecular carbon fullerenes [194]. During this period, coal ash was considered an important carbon source and new CNTs synthesized without catalyst contamination began to be considered as an alternative source. Today, C-FA is generally used instead of C-BA in the production of CNTs. Numerous means and carbon-rich C-FA-derived catalysts are employed in the synthesis of CNTs, and CNT ribbons [195]. An alternative in the production of carbon nanotubes is MSRW ash. Considering that the leading pyrolysis products gained from plastic wastes are suitable sources for CNT synthesis, it should be noted that productivity of CNTs will be exaggerated by factors like the type of feedstock, pyrolysis situations, and catalytic reaction circumstances [196]. Porous carbons are materials formed with several categories and physical structures like activated carbon and graphite. In the literature, many porous carbon products have been used to eliminate organic chemicals from waste-water [197]. Biomass ash is used as a carbon source in porous carbon's production and offers significant aid to this process [198].

In recent years, coal ashes (C-FA and C-BA) have attracted great attention as a valuable waste and have been used as a catalyst to foster efficiency, cut down costs, and preserve metal resources [199]. The various oxides contained in C-FA and C-BA make them ideal catalysts, increasing their trade benefit. Additionally, the mineralogical structure of this ash provides strength features needed for its usage [200]. The support materials usually consist of metal oxides, SiO_2, Al_2O_3, TiO_2, and MgO. The high aluminosilicate content of C-FA and C-BA makes them effective catalyst support materials due to their high stability in reactions [20]. Several studies have emphasized the use of catalysts to reduce the negative impacts of different ISRWs such as coal ash on human health and the environment [201,202]. The utilization of different waste materials such as coal ash as catalysts could alleviate different problems such as climate change by reducing greenhouse gas emissions. This could lead to a sustainable and green process for the conversion of carbon dioxide [203]. Also, the use of waste materials as catalysts could make significant contributions to reducing the management problems caused by production by limiting waste disposal. Especially catalysts (carbon dioxide methanation) produced with waste materials generated by combustion, such as coal ashes, could provide an alternative to non-renewable resources such as oil and natural gas and contribute significantly to the circular economy [204]. However, catalysts produced with the assistance of currently developed technologies and materials require significant know-how and experience. Significant progress can be achieved in many sectors thanks to catalysts that will be produced with a lower cost and easier methods in the future.

Aerogels, another application area of industrial ashes, are remarkable materials because of their properties like great surface area, high pore volume, low density, and thermal conductivity. They were initially created in the early 1900s due to the transitions between liquid–gas phases [28,205]. But, the complicated and expensive techniques encountered in the production of these materials have long limited the development of aerogels. Recycling of coal ashes has attracted attention [206]. The high silica–alumina content and brilliant protection performance of coal ash allow it to be evaluated as a valuable resource for silica aerogels. Using these materials continues in various application areas and has a wide potential for use, especially in adsorption and catalysts [207].

The contribution of industrial solid residual wastes to meeting the raw material needs in different sectors with traditional/innovative recycling techniques offers different advantages such as greatly reducing production costs and safe disposal of these wastes. However, the structural properties of these wastes may change depending on time and production conditions and the deficiencies in their combined use still constitute a disadvantage in this regard. Therefore, the future perspective of ISRW recycling should include correctly evaluating the characteristics of ashes from different regions with a combination of different methods and investigating their combined use; evaluating different pretreatments; implementing integrated toxicity assessment tests, cost–benefit analyses, and life cycle assessment; and keeping legal regulations constantly up to date [21,208,209].

6. Legal Regulations for Ash Management

Sustainable–safe management of industrial ashes covers various stages from production to disposal. These procedures involve transportation, storage, recycling, and disposal of waste [210]. Although storage is generally considered the most ideal method, it can lead to ecological problems such as groundwater pollution [211]. In addition, recycling or reuse of industrial solid ashes has the potential to reduce waste and offer economic gains. There are various regulations governing ISRW's management.

Regulations/guidelines for the management of industrial ash can vary across countries and regions. Some countries have strict regulations, while others have more flexible approaches. These rules include the disposal of the waste, the obligation of facilities to monitor groundwater, the implementation of appropriate closure and post-closure procedures, and the meeting of certain structural and engineering standards [212]. Currently, many regulations and legislations exist around the world to mitigate the problems associated with inadequate management and disposal of coal ash, which is abundantly generated in power plants and/or combustion plants. Notably, these regulations have been honed and finalized as a result of accidents (e.g., dam failures) related to the disposal of coal ash. Besides coal ashes, standardized regulation and legislation for municipal solid waste ashes and/or biomass ashes remain very limited. In this regard, a review of different countries' regulation and legislation for coal ash is presented below.

The Chinese government treats coal ash as solid industrial waste rather than hazardous waste, taking into account its potential uses. The National Development and Reform Commission (NDRC) and the Ministry of Ecology and Environment (MEE) are generally responsible for the control and supervision of coal ash nationwide. The NDRC issues guidelines to limit the disposal and ecological impact of coal ash, emphasizing its potential for recycling and reuse. The MEE, on the other hand, establishes guidelines and oversees implementation in urban and rural areas, with an emphasis on mitigating the environmental consequences of ash (e.g., air, soil, and water pollution) [213–215].

In the United States of America (USA), the Environmental Protection Agency (EPA) is the only organization that examines and limits the environmental and sociological impacts of coal ash. The agency publishes regulations and legislations for management and disposal of coal ash. EPA's final coal ash guidance was published in the Federal Register in 2015. The trigger for this guidance was the failure of coal ash dams in New York City, which resulted in the release of nearly 4 million metric tons of waste. Along with this accident, heavy metals (e.g., methylmercury) were released regionally, causing numerous environmental and sociological disasters. The USA has suffered significant consequences for improper management of coal ash and inadequate disposal conditions. To eliminate such problems, EPA continuously inspects and checks the compliance of coal ash management steps (e.g., storage, safety, surface and ground water control, and location of operations) in the facilities. Also, EPA's existing guidance has improved many practices such as the design, monitoring, and opening and closing of plants and has been transferred to the present day. This legislation covers all currently active new and old facilities [216,217].

India's energy production is largely dependent on coal, resulting in high volumes of coal ash. These ashes are not classified as hazardous waste by the government. However, improper disposal and storage of coal ash is becoming a major concern [218]. In this context, India's Ministry of Environment, Forests and Climate Change (MoEF) issued a directive in 1999 to limit the disposal of generated coal ash (from thermal power plants using coal and lignite). The targets set in this directive were updated and improved in 2003 and 2009. One of the objectives is to promote the use of coal ash from power generation (up to 100%) in construction materials to reduce their environmental and economic impact. Since the publication of the directive, the consumption of coal ash has increased from about 13.5% to 57.6%, although the desired targets have not been met [219].

The European Union (EU) has adopted different regulations and legislations to control the management and disposal of coal ash. Moreover, the scope of these guidelines has been expanded and accelerated in recent years due to disasters caused by the improper management and disposal of coal ash. The EU has different directives, such as the Industrial Emissions Directive (IED) and the Waste Framework Directive and Landfill Directive, to control and manage potential problems from coal ash. These directives allow environmental impacts to be limited by comprehensively assessing the process from the production of coal ash to its disposal. Under the IED, EU countries take measures to reduce the potential hazards of emissions, heavy metal releases, and other harmful pollutants from power plants and combustion plants. The IED also provides a comprehensive roadmap for monitoring and assessing emissions from coal ash disposal [220–222].

Coal ash is considered an industrial waste type in Australia and not subject to local regulation and legislation. Regulations and legislations for coal ash are similar to European Union and United States standards but vary significantly from state to state and from power plant to power plant within each state. As a result, access to much information is limited, such as closure of power plants and/or combustion plants, groundwater monitoring, and ash management and storage. State and regional regulations may relate to general environmental regulations rather than coal ash. The management and disposal of coal ash nationwide are therefore inadequate compared to other countries [223].

As mentioned above, many countries aim to manage coal ash properly within their own regulations and legislations. Although these guidelines differ depending on the country's approach to coal ash, the main objective is to reduce the damage caused by coal ash to the ecological system and to protect human health to a significant extent. In this common denominator, countries sometimes focus on reducing the problems associated with waste disposal, and sometimes encourage the utilization of these wastes as a source of raw materials. However, given the potential hazards of coal ash, regulations and legislations should not be limited to a few countries but should be applied globally. Furthermore, it is thought that steps should be taken to protect our future by improving existing rules and regulations and tightening inspections.

7. Conclusions

Today, industrial solid residual waste (ISRW) is becoming an indispensable element in a multitude of sectors, with their application areas continuing to expand. However, environmental, sociological, and economic problems arising from the traditional management of ISRWs are still a major concern. It is therefore becoming essential to treat ISRW in a sustainable manner, namely by recycling these wastes into value-added products. This review article examines the global impacts of ISRW generated from manufacturing energy and heat. It also reviews characteristics of these wastes and the various management strategies employed within the legal framework. Additionally, it highlights the utilization of ISRWs in novel areas compared to traditional management strategies and the transformation of ISRWs into products with higher economic and commercial value. Key interpretations of this review can be summarized below:

- ➢ Increasing energy demand and consumption induce large amounts of ISRW every year, depending on the type of fuel used and the characteristics of the raw material processed.
- ➢ ISRWs are notable for their heterogeneous structure and multicomponent organic and inorganic materials. These wastes may contain high levels of oxides and heavy metals, making them potential pollutants. Consequently, many ISWs are classified as hazardous wastes worldwide. Therefore, the comprehensive identification and characterization of ISWs are critical for sustainable management strategies.
- ➢ ISRWs are widely used in different construction applications, especially in concrete and cement. In addition, due to the rich content and strong physical properties of ISRWs, zeolite is utilized in different fields like adsorbents, glass, and soil improvement.
- ➢ Today, ISRWs are aimed to be transformed into products with high economic/commercial value compared to traditional methods. For example, ISRWs can be used in different fields such as geopolymers as an innovative and green alternative to cement, aerogel as insulation, and nanotubes as a chemical energy basis.
- ➢ A multitude of legislation and regulations exist to facilitate the sustainable management of ISRW, though these vary considerably by country/region. The aim of these legislation and regulations is to identify safe management strategies for ISRWs. The efficacy of legislation hinges on the cooperation and implementation rate of ISRW producers, local governments, municipalities, and other relevant organizations.

Consequently, the present paper draws attention to innovative and green uses of waste by illuminating the processes from the generation to disposal of ISWs. The necessity of utilizing ISRWs as a raw material source in different sectors and their recycling potential are emphasized. Innovative and green ISRW applications are expected to significantly reduce environmental and economic problems in the future. Especially with the use of advanced techniques in addition to traditional reuse/recycling areas for ISRWs, it is pointed out that ISRWs will be given a more sustainable perspective. However, given the difficulty of application, high costs, and limited knowledge of these methods, these methods currently fail to completely satisfy the sectoral needs. Such issues are thought to be addressed by the emergence of lower-cost alternative materials and/or methods that will increase the economic value of ISRWs through technological developments. The authors intend to present a comprehensive study that examines innovative uses and/or production methods of ISWs in the future. It is planned to consider and evaluate different types of waste in a similar way to this study. Thus, the utilization areas and production technologies of different types of wastes will be comprehensively investigated and their environmental and economic possibilities will be revealed.

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