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Enhancement of Sustainable Recycling Systems for Industrial Waste in South Korea via Hazardous Characteristics Analysis

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Abstract: The South Korean government has implemented an acceptance system to promote the high-quality recycling of waste. Industrial waste generators must provide "hazardous characteristics data" to recycling operators. Nonetheless, ~80% of industrial safety accidents in South Korea occur during recycling, most involving fire or explosions. Moreover, a gap in safety management exists during 'Circular Resource' acceptance if the target substance is not regarded as waste. In this study collected data on hazardous waste characteristics. From 62 waste generators, 72 waste samples were collected, accounting for most of the resources accepted for recycling, including waste synthetic polymers, slag, dust, waste sand, and waste foundry sand. Then, the hazardous characteristics, as stated in the Ministry of Environment notifications, were assessed. Leaching toxicity was detected in one slag sample and six dust samples. The Cd, Cu, As, Pb, Zn, Ni, Hg, F, and CN levels dissatisfied the Soil Contamination Warning Standard in 31 samples. Explosivity was not detected in any sample, whereas flammability was detected in one waste synthetic polymer sample. The results revealed 15 cases of potential flammability. Flammability is legally defined as below the criteria if the combustion speed criterion is not met. However, in the case of flame ignition, which could cause large fires and safety accidents, the relevant notification should be revised. In this study, we aimed to improve the gap between the hazardous waste management systems and industrial fields through actual measurements of hazardous characteristics. By doing so, we seek to contribute to the prevention of environmental and safety accidents. By continuously accumulating data and utilizing actual measurements, we aim to revise and enhance relevant regulations, ultimately improving the hazardous characteristics of waste management systems.

Keywords: hazardous characteristic; circular resource; inorganic industrial waste; industrial accident; waste recycling; flammability

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1. Introduction

In South Korea, where land is scarce and endowed resources are insufficient, efforts are being made to reduce waste generation and promote resource circulation via reusing and recycling waste in accordance with the Framework Act on Resources Circulation enacted in 2016 (implemented in 2018) [1]. The Acceptance System of Circular Resources, stated in the Framework Act on Resources Circulation, is a system that excludes high-quality wastes that are free from environmental and human hazards and have economic value from waste management, to allow liberal distribution and use. Currently, over 540 types of waste, including waste synthetic polymers, slag, dust, waste metals, and inorganic sludge, are accepted as recyclable resources. The number of acceptance cases has steadily increased since the Framework Act was implemented in 2018, suggesting that more wastes will be accepted as recyclable resources in the future [2,3]. However, once accepted as a recyclable resource, the target substance is no longer regarded as waste with potential indiscreet nationwide transfer, and as the current law in South Korea allows circular resources to be managed solely with reference to foreign substance criteria or heavy metal contents, there is a complete lack of data on hazardous waste characteristics.

Meanwhile, over 60 million tons of inorganic industrial waste are generated in South Korea, accounting for approximately 74% of the total industrial waste disposal. Among these, slag, dust, and waste foundry sand amounts to approximately 34 million tons, accounting for over 50% of the total inorganic industrial waste [4]. At present, over 95% of slag, dust, and waste foundry sand are recycled as raw materials in steel and cement manufacture, construction fill and cover materials, and road base materials [5,6]. However, safety accidents have occurred continuously in waste disposal, collection, transfer, and treatment, while the recycling rate has been high. According to the statistics by the National Fire Agency in South Korea, approximately 5000 accidents occurred due to waste; these include toxic gas generation, spontaneous combustion, and fire caused by explosive or water-reactive materials, of which approximately 88% of accidents occurred in facilities related to waste recycling [7]. Most such accidents are caused by inadequate data sharing on waste characteristics between the waste generator and recycling operator during recycling. Notably, the hazardous characteristics of waste (explosivity, flammability, oxidizability, corrosivity, water reactivity, pyrophoricity, leaching toxicity, ecotoxicity, and infectivity) are challenging in waste treatment and recycling, causing accidents and environmental problems.

The hazardous characteristics of waste have been managed in South Korea under "Notification of the Regulations on the Types of Wastes and Industries that Have to Identify Hazardous Characteristics" notified in 2016, and "Obligations to Prepare and Provide Hazard Information Data", a newly developed clause in the Waste Control Act (2017) [8]. As the notification on hazardous characteristics includes only 17 types among all the waste categories in management, there is a gap in the management scope. Additionally, inorganic waste, compared to other waste types, is commonly recycled as aggregate material for landfills, which significantly increases the likelihood of contact with soil or groundwater [9–11]. In fact, inorganic wastes release strongly alkaline leachate during recycling, which causes environmental problems [12–14].

Against this backdrop, this study presents data on the hazardous characteristics of synthetic polymer and inorganic industrial wastes among those with a high acceptance rate as recyclable resources in South Korea to prevent safety accidents during their handling.

This study is unique in that it focuses on the actual measurement of hazardous characteristics of industrial waste, contributing to the prevention of safety accidents through actual data. Our approach provides real-world insights into the hazardous properties of various waste materials. By analyzing 72 samples from 62 waste generators, including synthetic polymers, slag, and dust, this study offers a comprehensive understanding of the potential risks involved in waste recycling. This empirical approach not only enhances the accuracy of safety measures but also aids in the formulation of more effective waste management policies. The findings highlight the importance of considering actual hazardous characteristics data in safety regulations, thereby promoting safer recycling practices.

2. Literature Review

Various countries manage the hazardous characteristics of waste in different ways. The United Nations (UN), for example, categorizes hazardous characteristics into seven classes, from Class 1 to Class 9, and this system is designed to be compatible with the Basel Convention's categories of hazardous characteristics. The Basel Convention manages hazardous characteristics across 14 categories, from H1 to H13. These include two types of reactivity, five types of flammability, one type of corrosivity, three types of toxicity, two types of oxidizability, and one type of infectivity. In the United States, hazardous characteristics are broadly managed under four categories, but they differ in that they use a listing system based on waste and its characteristics. The European Union (EU) manages hazardous characteristics across 15 categories, from HP1 to HP15. In South Korea, hazardous characteristics are categorized into nine types, including explosiveness and flammability, and relevant regulations specify the generating industries and types of waste. Table 1 presents the hazardous characteristics of waste in different countries.

Table 1. Comparison of waste management status of hazardous characteristics.

Korea (9) [15]	**UN (7) [16]**	**Basel (14) [17]**	**EU (15) [18]**	**U.S.A (4) [19]**
Explosivity	Class 1 (Explosivity)	H1 (Explosivity)	HP1 (Explosivity)	Ignitability
Flammability (liquid)	Class 3 (Flammability [liquid])	H3 (Flammability [liquid])	HP3 (Flammability)	
Flammability (solid)	Class 4 (Flammability [solid])	H4.1 (Flammability [solid])		
Pyrophoricity		H4.2 (Pyrophoricity)		
Water reactivity		H4.3 (Water reactivity)		Reactivity
Oxidizability	Class 5 (Oxidizability and Organic peroxide)	H5.1 (Oxidizability)	HP2 (Oxidizability)	
-		H5.2 (Organic peroxide)	HP1, HP3	
-	Class 6 (Toxicity and Infectious substances)	H6.1 (Poisonous [acute])	HP6 (Poisonous [acute])	Toxicity
Infectivity		H6.2 (Infectivity)	HP9 (Infectivity)	-
Corrosivity	Class 8 (Corrosivity)	H8 (Corrosivity)	HP4 (Irritant) HP8 (Corrosivity)	Corrosivity
-	Class 9 (Miscellaneous dangerous substances & articles)	H10 (Water reactivity or oxidizability)	HP12 (Water reactivity or oxidizability)	Reactivity
-		H11 (Toxicity)	HP4, HP5, HP7, HP10, HP11, HP13	Toxicity
Ecotoxicity		H12 (Ecotoxicity)	HP14 (Ecotoxicity)	
-		H13 (etc)	HP15 (etc)	-
Leaching Toxicity	-	-	-	Toxicity

3. Materials and Methods

3.1. Materials

Approximately 4.15 million cases from the 2021 Allbaro system were statistically analyzed to collect samples of synthetic polymer and inorganic industrial wastes [20]. The disposal of inorganic industrial wastes was reported by 4186 waste generators in total, and approximately 22,000 cases of waste synthetic polymers were reported by 1600 waste generators. Among the inorganic industrial wastes, dust was generated by the highest number of facilities, at n = 2011. The disposal of ≥99% of slag and waste foundry sand was as general industrial waste, and slag, in particular, had a ≥86% disposal rate by the top 10 waste generators with the highest generation of slag (See Figure 1b). Considering the waste generator and the amount of generated waste, 72 samples were collected from 62 facilities. For the sample collection, the Waste Pollution Standard Method was followed; the details are given in Figures 1 and 2 and Table 2.

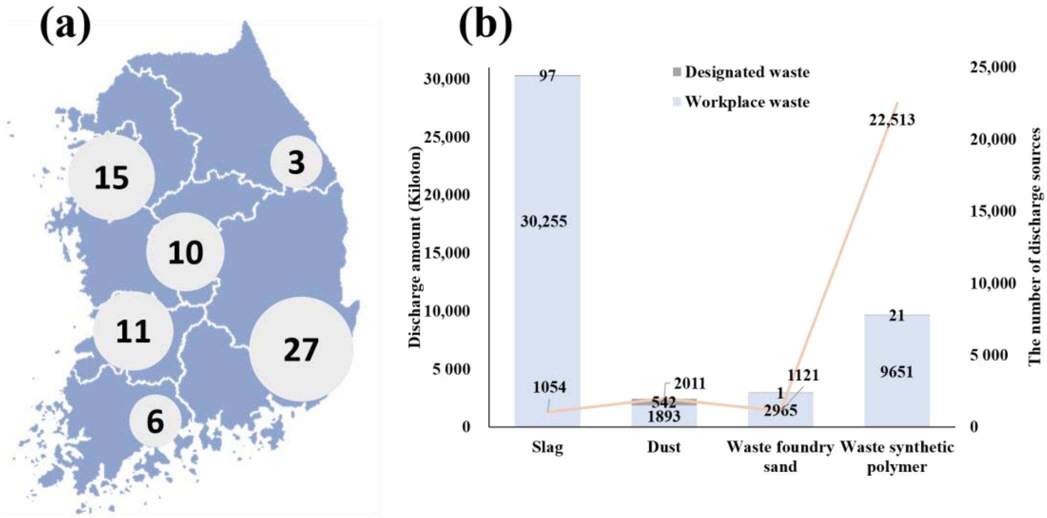

Figure 1. (**a**): Sampling location(The numbers present the number of samples), (**b**): Amount of sample waste discharge.

Figure 2. Sample images.

Table 2. Details of waste sample for this study.

Waste Type	Classification	Number of Samples		
		Designated Waste	Workplace Waste	Total
Slag	Steel slag	-	2	2
	Furnace slag	-	1	1
	Lead heat treatment metallurgical process slag	1	-	1
	Slag not otherwise specified	-	2	2
Dust	Dust	6	-	6
	Dust not otherwise specified	-	15	15
Waste foundry sand	Chemical caking waste foundry sand	-	5	5
	Clay caking waste foundry sand	-	2	2
	Sandblast sand	-	1	1
	Waste sand not otherwise specified	-	5	5

Table 2. *Cont.*

Waste Type	Classification	Number of Samples		
		Designated Waste	Workplace Waste	Total
Waste synthetic polymer	Waste Polypropylene	2	-	2
	Waste polyvinyl chloride resin	1	1	2
	Waste synthetic rubber	3	3	6
	Waste synthetic resin	-	6	6
	Waste styrofoam	-	1	1
	Waste foamed synthetic resin	-	2	2
	Plastic waste packaging material	-	1	1
	Waste fish net	-	1	1
	Waste polyurethane foams	-	1	1
	Waste polyethylene	-	1	1
	Waste synthetic polymer compounds not otherwise specified	4	5	9
			Total	72

3.2. Methods

The current law in South Korea stipulates that the hazardous characteristics of waste be assessed in recycling 17 waste types disposed of by the facilities stated in the regulatory notification “Notification of the Regulations on the Types of Wastes and Industries that Have to Identify Hazardous Characteristics” [16]. However, as the waste accepted as a circular resource is handled no longer as waste but as a general product, it could cause a potential gap in safety management. Thus, this study aimed to resolve this gap by collecting data on hazardous waste characteristics based on actual measurements. Notably, for slag, the notification states that only the leaching toxicity and water reactivity be assessed, but the corrosivity was additionally analyzed in this study considering the potential release of strongly alkaline leachate upon contact with water.

In South Korea, there are nine hazardous characteristics (See Table 1). The relevant notifications specify which hazardous characteristics need to be checked according to the generating industries and waste classifications, and Table 3 shows the hazardous characteristics that need to be checked for the waste used in this study. This study focuses on analyzing waste generated from industries not specified in the notifications, and waste from other than the applicable industries was not used.

Table 3. Hazardous characteristics list for each waste type in South Korean regulations.

Waste Type	Generating Industry	Hazardous Characteristic
Slag	a. Other Non-Ferrous Metal Smelting, Refining, and Alloy Manufacturing (24219) b. Copper Rolling, Extrusion, and Drawing Products Manufacturing (24221) c. Other Primary Non-Ferrous Metal Manufacturing (2429)	Leaching toxicity, water-reactivity, corrosivity [a]
Dust	a. Other Non-Ferrous Metal Smelting, Refining, and Alloy Manufacturing (24219)	Leaching toxicity, water-reactivity, corrosivity, explosivity, flammability
Waste foundry sand	a. Cast Iron Foundry (24311)	Leaching toxicity
Waste synthetic polymer	a. Synthetic Rubber Manufacturing (20301) b. Synthetic Resins and Other Plastic Materials Manufacturing (20302)	Flammability

[a] Although slags are not considered corrosive in regulations, they were analyzed in this study because the pH of some slags is too high.

3.3. Leaching Toxicity

The Waste Standard Test Criteria were followed to measure the leaching toxicity of the samples. In the analysis, the seven regulated elements (As, Cd, Cr^{6+}, Cu, Pb, Hg, and CN) stated in Annex 1 of the Wastes Control Act and 10 additional unregulated elements (Cr, Zn, Ni, Ba, Be, Sb, Se, Sr, V, and Mo) were tested in consideration of human and environmental hazards. Among the elements, Cr^{6+} and CN were analyzed using ultraviolet–visible spectroscopy (UV-Vis, Lambda 365, PerkinElmer, Waltham, MA, USA), Hg was analyzed using atomic absorption spectrometry (AAs, PinAAcle 900T, PerkinElmer), and the remaining elements were analyzed using inductively coupled plasma-optical emission spectrometry (ICP-OES, Avio™550Max, PerkinElmer). Details about test method indicate in Table 4.

Table 4. Details of leaching toxicity test method.

Element	Test Method [21]
As, Cd, Cu, Pb, Cr, Zn, Ni, Ba, Be, Sb, Se, Sr, V, Mo	ES 06400.2 (Inductively coupled plasma-atomic emission spectrometry)
CN	ES 06351.1 (CN-UV-visible spectrometry)
Hg	ES 06404.1a (Hg-cold vapor-atomic absorption spectrophotometry)
Cr^{6+}	ES 06407.3a (Cr^{6+}-UV-visible spectrometry)

3.4. Heavy Metal Contents

While inorganic wastes vary according to the waste generator and process, the probability that they may contain hazardous heavy metals is relatively high [22–24]. Additionally, wastes are typically recycled mostly as construction fill and road base materials for burial, so they often come into contact with the soil. Hence, it is necessary to collect content analysis data to reflect the concerns of soil pollution caused by the respective waste recycling and take preventive measures. Table 5 shows EPA method and the criteria about leaching toxicity and heavy metal contents. In the absence of criteria on waste contents in South Korea, the assessment was conducted across three regions: 1, 2, and 3, divided according to the Soil Contamination Warning Standard in the Soil Environment Conservation Act. The Soil Pollution Standard Method and the EPA methods were used in the analysis regarding 16 items in total, with the addition of fluorine in the leaching test.

Table 5. Criteria for leaching toxicity and heavy metal contents in South Korea regulation.

Subdivided / Compound	Leaching Criteria [25] (mg/L)	Heavy Metal Content Criteria [26] (mg/kg)			EPA Method [27–31]
	Designated Waste	Area 1	Area 2	Area 3	
Arsenic (As)	1.5	25	50	200	EPA 3050B
Copper (Cu)	3.0	150	500	2000	EPA 3050B
Mercury (Hg)	0.005	4	10	20	EPA 7471a
Cadmium (Cd)	0.3	4	10	60	EPA 3050B
Lead (Pb)	3.0	200	400	700	EPA 3050B
Hexavalent chromium (Cr^{6+})	1.5	5	15	40	EPA 3060a
Cyanides (CN)	1.0	2	2	120	EPA 9013A
Zinc (Zn)	N/A	300	600	2000	EPA 3050B

Table 5. *Cont.*

Compound \ Subdivided	Leaching Criteria [25] (mg/L)	Heavy Metal Content Criteria [26] (mg/kg)			EPA Method [27–31]
	Designated Waste	**Area 1**	**Area 2**	**Area 3**	
Nickel (Ni)	N/A	100	200	500	EPA 3050B
Fluorine (F)	N/A	400	400	800	EPA 5050
Chromium (Cr) Beryllium (Be) Selenium (Se) Vanadium (V) Molybdenum (Mo) Strontium (Sr) Barium (Ba) Antimony (Sb)	N/A	N/A	N/A	N/A	EPA 3050 B

N/A: Not Available.

3.5. Hazardous Characteristics

The Waste Pollution Standard Method was followed to measure the hazardous characteristics of waste. The details of the test method are given in Table 6. In South Korea, the Waste Pollution Standard Method classifies only the presence or absence of hazardous characteristics, but for certain items, the possibility of secondary safety accidents with potential hazard concerns should be considered rather than the simple presence or absence of data. For instance, in the case of flammability, the risk of safety accidents is sufficiently high even if the combustion occurs at only 50 mm after 45 s rather than at 100 mm within 45 s. Thus, this study extended and interpreted an additional concern regarding potential hazardous characteristics. Figure 3 presents a schematic diagram of the analysis of hazardous waste characteristics. The symbol ◎ means that the hazardous characteristic has been detected exceeding the criteria, △ means that while it does not exceed the criteria, there is a high possibility of the hazardous characteritic being present, and X means that no hazardous characteritic is detected.

Table 6. Detail of hazardous characteristics test method.

Hazardous Characteristic	Test Method [21]
Corrosivity (Solid)	ES 06304.1 (pH—Electrometric method) ES 06803.1 (Test methods for corrosion of metals)
Explosivity (Solid)	ES 06801.1b (Test method of explosivity)
Water reactivity	ES 06804.1 (Test methods for substances which, in contact with water, emit flammable gases)
Flammability (Solid)	ES 06802.4 (Test methods for flammability of solids)

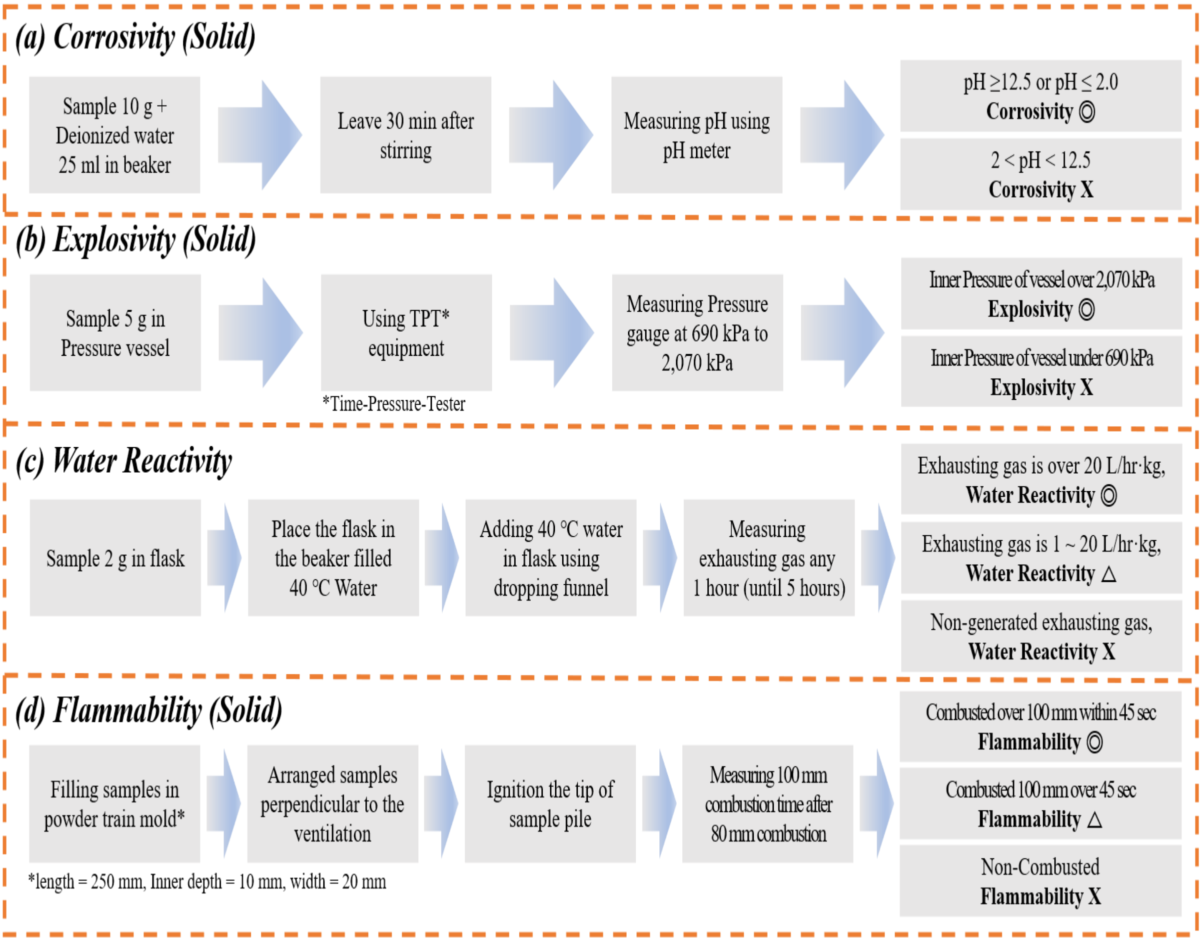

Figure 3. Schematic diagram of hazardous characteristics test method.

4. Results and Discussion

4.1. Leaching Test

Figure 4 shows the leaching toxicity for the seven regulated elements. Among the 40 samples, the leaching toxicities of one slag and six dust samples were above the criteria.

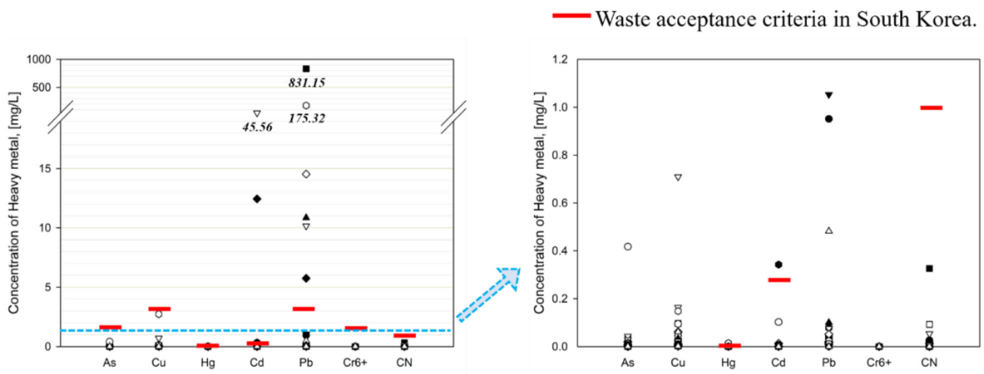

Figure 4. Result of regulated element leaching test (1 slag, 6 dust samples were higher levels than the criteria. All of them are discharged as designated waste).

One slag and five dust samples had higher Pb levels than the criteria. The slag generator was for the lead and zinc smelting, refining, and alloying industry, and the detected level of Pb was 831 mg/L. The generator manufactured lead ingot through metal recovery using waste batteries. It is conjectured that, in the lead ingot manufacturing process, the slag residues, after lead recovery via gravity separation, were discharged and this lead to the leaching of a large amount of lead. The corresponding waste was confirmed to be appropriately disposed of as designated waste.

Dust generators was mostly due to metal production and iron and steel making, including the inorganic dye and other metal oxide industry, the iron-making industry, the primary steel-making industry, and the steam, cold and warm water, and air-control-supplying industry. The composition of dust generated by iron-making varies according to the applied raw material and operation conditions, while the main constituents include the oxides of Fe, Zn, and Pb. It is, thus, conjectured that lead was detected due to the industrial characteristics.

In one dust sample, the level of Hg exceeded the criteria. The corresponding generator was a power plant using solid recovered fuel (SRF) produced from waste plastic and vinyl materials, and the result was attributed to the effect of fuel combustion. The level of Hg in fly ash increases as the SRF ratio increases upon mixed fuel combustion. By reacting with Cl- in the filter cake layer of the bag filter, Hg was partially released as gas-phase $HgCl_2$ and partially adsorbed to the ash layer to be released as dust [32].

In three dust samples, the level of Cd exceeded the criteria, and the corresponding generators were from the iron and steel-making industries. It is likely that the Cd contained in the raw material upon the fusion of metal material in the electric arc furnace was present in the released dust. The dust dissatisfying the leaching criteria was appropriately disposed of as designated waste.

Figure 5 shows the result of analyzing the 10 unregulated elements with potential hazards. While most were non-detectable or detectable in trace amounts, certain samples contained up to 315 mg/L of Zn and up to 340 mg/L of Ba. The excessive level of Zn could be attributed to the characteristics of the steel-making and metal-production industries. The sample with the excessive level of Ba was from a waste-battery-recycling operator, and the leaching is likely due to the effect of $BaSO_4$ in the anode of the batteries [33]. The effects of Zn and Ba on the human body are as follows: Excessive Zn exposure causes gastrointestinal disorders and cardiovascular disease [34,35], and those residing in an environment with Ba exposure show high probabilities of renal and respiratory disorders [36]. Hence, utmost care should be taken when handling waste associated with Zn and Ba materials.

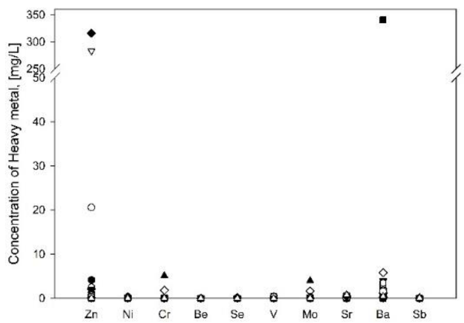

Figure 5. Result of unregulated element leaching test. 3 samples were leachate with high levels of Zn and Ba.

4.2. Heavy Metal Contents

Table 7 demonstrates the results of analyzing the contents of heavy metals found in industrial wastes in South Korea. As previously mentioned, references were made to the Soil Contamination Warning Standard in analyzing the waste samples due to the lack of relevant criteria on heavy metal contents in South Korea (See Table 5). The threshold was exceeded in 12 cases of Cd, 23 of Cu, five of As, 13 of Pb, 30 of Zn, nine of Ni, four of Hg, nine of F, and one of cyanides. The single region criterion of the Criteria on Potential Soil Pollution was exceeded in four slag samples, 16 dust samples, 12 waste foundry sand samples, and nine waste synthetic polymer samples. The Zn content was particularly high in dust and waste synthetic polymer samples. In the case of dust, the high Zn content could be attributed to the process characteristics of iron and steel making and metal manufacturing. Regarding waste synthetic polymers, it was mainly the rubber samples that displayed a high Zn content, presumably because the production includes the addition of nano-ZnO for rubber stability and longevity [37]. The results of the waste content analysis should be used as a reference to prevent soil or nearby river pollution.

Table 7. Results of heavy metal content test.

Compound	Samples (mg/kg)			
	Slag (n = 6)	**Dust (n = 21)**	**Waste Foundry Sand (n = 13)**	**Waste Synthetic Polymer (n = 32)**
Arsenic (As)	N.D.~207.06	N.D.~42.73	N.D.~30.16	N.D.~27.83
Copper (Cu)	11.3~1036.3	3.4~5548.2	4~20,477.3	N.D.~579.7
Mercury (Hg)	N.D.~0.43	N.D.~10.97	N.D.~0.62	N.D.~4.23
Cadmium (Cd)	N.D.~10.09	N.D.~4000.39	N.D.~4.89	N.D.~20.14
Lead (Pb)	N.D.~24,984.4	3.4~33,493.1	4.1~134.6	N.D.~15,197.3
Hexavalent chromium (Cr^{6+})	N.D.	N.D.~3	N.D.	N.D.
Cyanides (CN)	N.D.~0.9	N.D.~11.5	N.D.~1.4	N.D.
Zinc (Zn)	4~1074.5	36.9~960,045.8	35.1~9804	1~13,593.4
Nickel (Ni)	13.4~179.5	1.6~656.3	2.9~994.5	0.2~22.5
Fluorine (F)	N.D.~311	68~7808	N.D.~3218	N.D.~53
Total chromium (Cr)	41~2121.5	2.3~4617.2	4.3~619.5	0.6~55.8
Beryllium (Be)	N.D.	N.D.	N.D.	N.D.~0.1
Selenium (Se)	N.D.~32.2	N.D.~36.8	N.D.	N.D.~10.6
Vanadium (V)	17.1~227.5	1.1~145.5	5.1~217.6	N.D.~17.4
Molybdenum (Mo)	N.D.~20.2	N.D.~95.5	N.D.~15.1	N.D.
Strontium (Sr)	16.8~2289.7	2.5~289.8	N.D.~282.3	N.D.
Barium (Ba)	13~1450.3	6.6~867.4	5.8~243.2	N.D.~72.6
Antimony (Sb)	2.1~717.3	N.D.~2393.6	N.D.~421.4	N.D.~4005.2

4.3. Hazardous Characteristics

Table 8 shows the analyzed hazardous characteristics, including explosivity, flammability, water reactivity, and corrosivity. The data exclude waste foundry sand, as the relevant notification requires only assessing the leaching toxicity. In the case of explosivity, all 21 tested samples demonstrated a non-detectable level.

Table 8. Results of hazardous characteristic test.

	Corrosivity			**Flammability**			**Explosivity**			**Water reactivity**		
	◎	△	x	◎	△	x	◎	△	x	◎	△	x
Slag	1	-	5	-	-	-	-	-	-	-	1	5
Dust	1	-	20	-	-	21	-	-	21	-	1	20
Waste synthetic polymer	-	-	-	1	15	16	-	-	-	-	-	-

4.4. Water Reactivity

The level of water reactivity indicated concerns about potential hazards in one dust (steel industry) sample and one slag (power plant) sample. While the Standard Test Criteria state that waste is water reactive if ≥20 L/kg·h of flammable gas is produced, the samples in this study demonstrated a reactivity of 8 L/kg·h and 1 L/kg·h, respectively, so did not meet the criteria. The cause of water reactivity was primarily attributed to the reaction between water and the CaO contained in the slag or dust from the steel-making process and power-plant operation.

In general, sulfur (S) and oxygen (O) are handled as impurities in steel making. FeMn is used to remove such impurities and ensure durability and anti-corrosivity by adding Mn to the steel [38]. However, dephosphorization should be performed, as the phosphorous (P) constituent of FeMn is also an impurity that reduces the steel quality. For dephosphorization, $BaCO_3$, BaO, BaF_2, $BaCl_2$, CaO, CaF_2, Na_2CO_3, or Li_2CO_3 is mainly used; these agents remove phosphorous by forming a phosphoric compound (Ca_3P_2, Mg_3P_2, $Ba_3(PO_4)_2$, etc.) [39]. Despite variations according to the process conditions, the slag produced in such processes is generally likely to be disposed of in a form containing the oxides of alkaline earth metals (Ba, Mg, Ca, etc.), and the respective oxide is thought to undergo an exothermic reaction with water to produce gas.

An XRF analysis was performed on the waste (slag and dust) samples tested for water reactivity for more accurate causal analysis(See Figure 6). The samples commonly contained CaO, and in addition to the oxides of alkaline earth metals Ca and Mg, SiO_2 and Fe_2O_3 were the main constituents. Based on this analysis, the produced gas was attributed to the reaction between CaO and water. The level of gas production was the highest for the slag from the power plant, although the amount of CaO was relatively small. This may be due to the difference in the content of free CaO with high reactivity resulting from the waste-storage conditions and duration [40]. While an immersion expansion test is necessary to measure free CaO, it is difficult to quantify free CaO with this method; hence, a follow-up study should be conducted. Additionally, the gas produced in the water reactivity test was assessed for flammability; it was unreactive in the flame test, and the produced gas is, thus, presumed to be not flammable gas but steam produced in the exothermic reaction between CaO and H_2O.

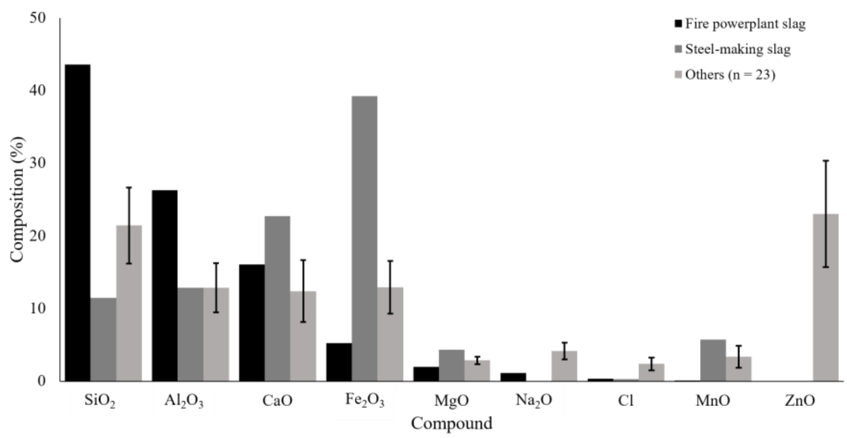

Figure 6. XRF data of samples.

4.5. Corrosivity

Corrosivity was detected in one slag and one dust sample. Both samples were strongly alkaline, at pH 12.5 or above, exhibiting corrosivity. The slag sample was disposed of after a lead and zinc smelting process. In the process, lime is added as a subsidiary material, and the slag at disposal contains an abundance of free CaO to release strongly alkaline leachate upon reaction with water. The current Waste Control Act in South Korea states that the waste be disposed of and recycled after a period of aging through contact with air or water sprinkling, but in a previous study, water sprinkling alone did not lower the pH [41]. In recycling slag, therefore, utmost care should be taken on-site to prevent the slag from contacting rainwater. The chemical composition of slag generally contains CaO, SiO_2, MnO, and MgO [42], most of which are alkaline with an effect on pH. The one case of dust was a waste disposed of by a lime and plaster manufacturer, and the high pH was attributable to the lime content. For a more accurate causal analysis, an XRF analysis was performed, and the results are shown Figure 7. The data show that the slag sample had a substantial CaO content, and the dust sample was composed mainly of Fe_2O3, Na_2O, and ZnO. The pH is, thus, likely to have been high due to the alkaline constituents.

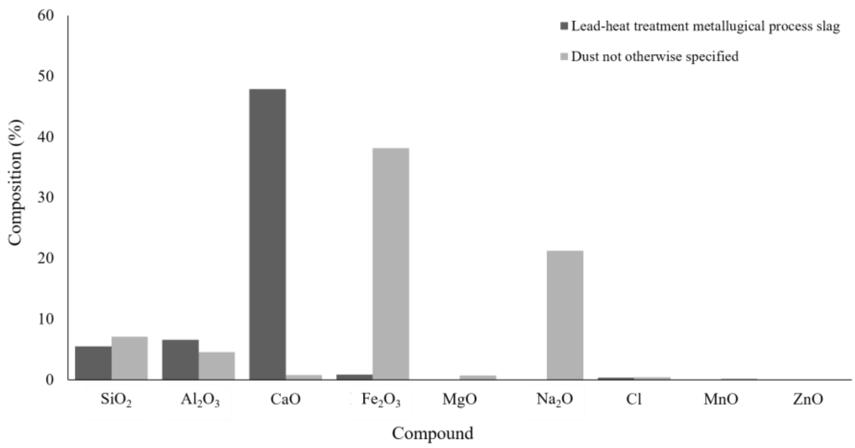

Figure 7. XRF data of corrosive samples.

4.6. Flammability

Figure 8 shows the results of flammability test. Among the tested waste samples, no dust samples exhibited flammability. For the waste synthetic polymers, one sample exceed the criteria, 15 were below the criteria but potentially flammable, and 16 were non-flammable. In assessing the flammability, the applied train mold should show combustion at 100 mm within 45 s to be designated as flammable. The potentially flammable samples displayed flame ignition but did not meet the combustion speed criteria. The results suggested that, while most samples were not flammable based on the current criteria, many substances are likely to be flammable based on the actual measurements of hazardous characteristics. Care should be taken in waste management due to the possibility of safety accidents upon the flame ignition of waste, which could advance to a large fire.

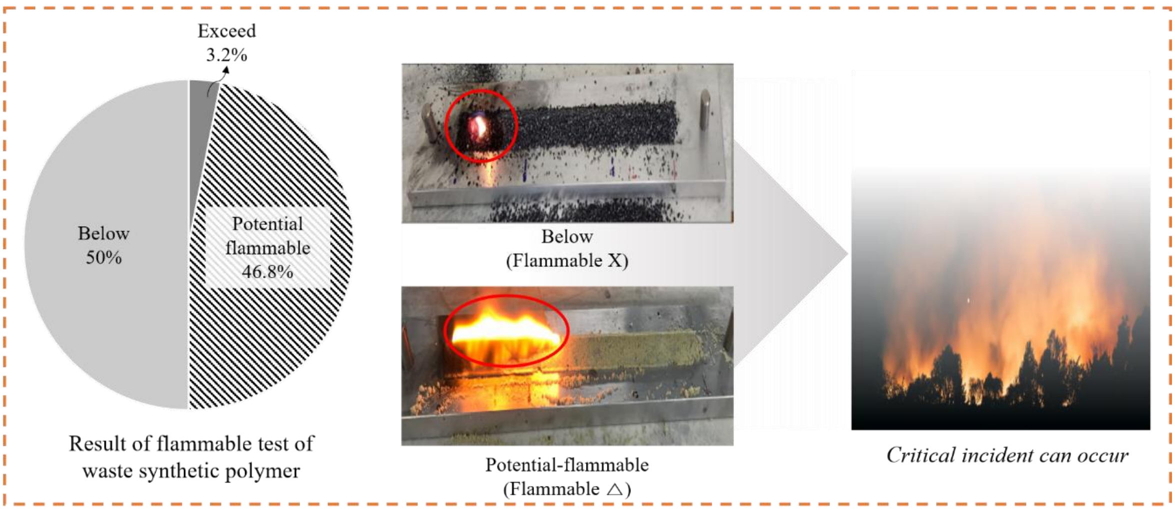

Figure 8. Results of flammability test.

5. Conclusions

This study analyzed the hazardous characteristics of waste for the safe recycling of slag, dust, waste sand, waste foundry sand, and waste synthetic polymers accepted as recyclable resources in South Korea, with a causal analysis. The conclusions are as follows.

1. Leaching toxicity was analyzed for six slag samples, 21 dust samples, 13 waste sand and waste foundry sand samples, and 32 waste synthetic polymer samples. Leaching toxicity was detected in one slag sample (with excessive Pb) and six dust samples (excessive Pb, Hg, and Cd). All these samples were disposed of as designated waste. Among the unregulated elements, Zn and Ba were abundant in certain samples, which implied a need for precautions.
2. In the content analysis, the levels of Cd, Cu, As, Pb, Zn, Ni, Hg, F, and CN dissatisfied the single region criterion of the Criteria on Potential Soil Pollution in 31 samples. This implied a need for utmost care in the storage and recycling in an area potentially in contact with the soil or groundwater.
3. Explosivity was not detected in any of the tested samples, whereas flammability was detected in one waste synthetic polymer sample with 15 samples, raising concerns about potential flammability. The current law defines flammability as below the criteria if the combustion speed criterion is dissatisfied. However, in the case of flame ignition, which could cause large fires and safety accidents, further study is needed to amend the related notification.
4. Two samples demonstrated gas production in the water reactivity test, but the gas was determined not to be caused by water reactivity in the flame test. Additionally, two samples exhibited corrosivity due to their strongly alkaline nature (pH 12.5 or above). The disposal of inorganic industrial wastes in South Korea is largely accounted for by the iron-, steel-, and metal-manufacturing industries. Hence, there is a risk of potential corrosivity due to the characteristic content of alkaline earth metals in such waste generators, and care should be taken in handling wastes with special regard to environmental accidents.
5. This study aims to manage the hazardous characteristics of waste based on actual data, considering that there may be cases where the waste does not meet the hazardous characteristic criteria but still has potential corrosivity or flammability issues due to the industrial field. However, it is practically challenging to measure all waste. Therefore, further study is required to avoid underestimation of the hazardous characteristics of waste. In the future, these actual data would be applied to revise continuously accumulate data and conduct follow-up studies to revise and supplement the relevant notifications.

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