RSC Advances

PAPER

Cite this: *RSC Adv.*, 2026, **16**, 18210

Assessing the environmental impact of electric arc furnace slags: comprehensive characterization and leaching analysis

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All over the world, a large amount of electric arc furnace (EAF) slag is produced in the iron and steel industries every year, and the correct management of these by-products is the main problem of these industries. Therefore, the complete characterization of these slags is effective in choosing the correct method for their management. This study focused on the characteristics of EAF steel slag in terms of physicochemical, structural, morphological, surface, and slag leaching behavior. Accurate determination of the metal content of these slags showed various base and precious metals including Fe, Al, Li, Mn, Si, Ba, Ti, V, and Zn. The slag consisted of different crystalline phases, which mostly contained iron, calcium, and silica oxides. Also, the slag structure was made up of various functional groups. The acid neutralization capacity (ANC) test on the slag sample showed that a high amount of acid is needed to reduce the pH of the EAF slag. The leaching behavior of metals through the TCLP, SPLP, and WET methods also showed that the slag is not considered hazardous waste, and the values obtained are within the EPA standard range. Overall, the findings provide a comprehensive understanding of EAF slag properties and offer valuable guidance for the safe management and potential reuse in industrial and environmental applications of this by-product.

Received 13th November 2025
Accepted 30th January 2026

DOI: 10.1039/d5ra08759g

rsc.li/rsc-advances

1. Introduction

The presence of steel industries is of paramount importance for the economic development of many countries.[1] These industries provide the raw materials necessary for industrial facilities, buildings, vehicles, and a multitude of other daily necessities.[1,2]

The by-products of these industries include steel slag, dust, and sludge.[3–5] In 2019, it was estimated that about 190 to 290 million tons of slag is produced annually from the steel industry across the world.[6] Therefore, special attention is paid to the valuation of these slags. Four types of slag, including electric arc furnace slag (EAF), blast furnace slag (BF), basic oxygen furnace (BOF), and processed Linz–Donawitz slag (LD-slag), are by-products of these industries.[7,8]

EAF steel slag is a by-product of the conversion of scrap iron and steel into steel in electric arc furnaces. This process entails the melting of scrap materials using the heat generated by an electric arc, which is in turn created by an electric current.[3,9] In the process of slag production by EAF, between 10% and 15–20% of slag was produced per ton of steel.[10,11] So about 100–160 kg of EAF slag was formed per ton of molten steel.[12]

The chemical composition of the produced slag is influenced by various factors, including the processing conditions and the composition of the scrap material fed into the electric arc furnace.[12] In general, considering that the input feed to the electric arc furnace is different, the chemical composition of the slag produced by the EAF is also different.[3] Usually, EAF slag contains 22–60% CaO, 3–14% Al_2O_3, 10–40% FeO, 3–13% MgO, and 6–34% SiO_2.[10] These production slags can be considered as potential sources of valuable metals.[13] These are secondary sources of metals rather than final scraps and are used as source material in various applications.[7]

Steel slag has various applications due to its various properties such as porous structure, high mechanical strength, high ion exchangeability, and high surface area.[12] Various applications of slag include: it is used as an absorbent or filter in wastewater treatment plants,[8,14] fertilizer in agriculture, soil improvers,[15] changing the acidity of soil and water sources,[7] building materials, road construction, and making ceramics.[16,17] However, despite these advantages, concerns remain regarding the potential environmental risks associated with slag utilization and disposal.

On the other hand, considering that production slag contains a significant amount of heavy and toxic metals, the release of these metals may lead to environmental damage.[16]

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Due to the presence of heavy metals in slags, in some countries, like Indonesia, EAF slag is classified as hazardous waste due to its composition.[18,19] In addition, in many developing countries, slag that is not reused is generally disposed of in landfills that are not closed or separated from the surrounding environment[1] or it accumulates in steel factories for a long time.[18] The release of elements or heavy metals from steel slags that contribute to the production of alkalinity can cause environmental problems such as soil and water pollution.[1,11] For this reason, steel slag should be refined by selecting the proper methods to reduce the metal content in it.[18]

Various questions are raised about the correct method of EAF steel slag landfill, the correct recycling of metals in the slag, and the selection of the correct slag management method in steelmaking industries.[18] So, to answer the questions raised in this field, there must first be a correct and complete knowledge of steel slag.

Although numerous studies have investigated specific properties or applications of steel slag, there remains a lack of integrated studies that simultaneously address the physicochemical, structural, surface properties and leaching behavior of EAF slag under conditions representative of both landfill disposal and natural precipitation. This knowledge gap hinders the development of reliable, site-specific strategies for slag management and reuse.

The novelty of the present study lies in the comprehensive and systematic evaluation of EAF steel slag with advanced structural, morphological, and surface analyses, various leaching methods, and evaluation of the acid neutralization capacity of the slag. This integrated approach enables a more reliable evaluation of the environmental safety and management potential of EAF slag. To achieve these objectives, the present research focuses on: (1) determining the elements and metals in the slag and conducting X-ray diffraction (XRD), field emission scanning electron microscope (FESEM), Fourier transform infrared spectrometer (FTIR), and energy dispersive X-ray spectrometer (EDX-mapping) tests. (2) Characteristics of EAF steel slag under landfill and rainfall conditions by analyzing the effect of different leaching tests on the steel slag samples, namely, toxicity characteristic leaching procedure (TCLP), synthetic precipitation leaching procedure (SPLP), and waste extraction test (WET) tests. (3) Determination of pH and acid neutralization capacity (ANC) of slags.

2. Materials and methods

2.1. Preparation of EAF steel slags

The electric arc furnace slag analyzed in this study was obtained from Mobarakeh Steel Company (Isfahan, Iran), one of the largest integrated steel producers in the country Iran, operating industrial-scale EAF steelmaking facilities. This slag contains varying percentages of oxides of aluminum, iron, magnesium, manganese, and other elements.[20] The slags produced from the eight EAFs were slowly cooled in the presence of air in the slag accumulation site. Then, samples were randomly collected from several areas of the slag accumulation site in the company and mixed together.[21] To ensure that environmental pollutants do not enter the sample, the final slag was transferred to the laboratory in a polyethylene plastic bag. The prepared slag samples were first air dried for 72 h, then the samples were crushed and softened with a ball mill and passed through a #200 mesh sieve (particle size of <74 μm). Finally, the prepared sample (slag with a particle size of <74 μm) was kept in a sealed container and used for all the tests.[22]

2.2. Chemical digestion and elemental analysis of EAF steel slags

The chemical composition of EAF steel slag after alkaline digestion was determined using an inductively coupled plasma optical emission spectrometer (ICP-OES) (Vistapro, Varian, Australia).

To alkaline digestion of EAF steel slag powder, first, a mixture of H_3BO_3 and $NaKCO_3$ was added to 0.25 gr of slag powder in a platinum crucible, and then it was heated on a flame for about 30 min. After that, the crucible was placed in an electric furnace at a temperature of 950 °C for 30 min. Then the molten material in the crucible was cooled, and 20 ml of hydrochloric acid with a ratio of 1 : 1 and 5 ml of aqua regia were added to it to dissolve.[18,23,24] Finally, the solution was filtered, and the concentration of metals in it was determined by ICP-OES. Samples were measured three times for elemental analysis and then the mean values were reported.

2.3. Characterization of EAF steel slags using various analyses

2.3.1. Initial pH determination. To determine the acidic, neutral, or alkaline nature of EAF steel slag, 1 gr of the powder sample was added to 50 ml of distilled water and then placed in a shaker incubator for 24 h at 30 °C at a speed of 140 rpm.[25] The initial pH of the slag powder sample was measured with a digital multimeter (WTW, model pH 3110, Weilheim, Germany). This pH measurement method was chosen to represent conservative leaching conditions with sufficient contact between the slag and the aqueous phase, thereby allowing for the dissolution of reactive alkali phases present in the slag. The pH measurements of the slag samples were conducted in triplicate, and the results are reported as mean values.

2.3.2. X-ray diffraction spectrometry. To identify phase structures and analyze the crystal structure of EAF steel slag, X-ray diffractometer PW1730, Philips, Netherland was carried out using Cu-Kα radiation with a step size of 0.05 from range: $10° \leq 2\theta \leq 80°$, with a current of 30 mA and a voltage of 40 kV.

2.3.3. FTIR analysis. To identify functional groups and determine the chemical structure of EAF steel slag, the infrared spectrometer AVATAR, Thermo, USA was used in the wavelength range of 400 to 4000 cm^{-1} at room temperature.

2.3.4. Surface morphology and EDX analysis. A field emission scanning electron microscope equipped with an energy dispersive X-ray spectrometer (FE-SEM; MIRA3 TESCAN-XMU, Czech Republic) was used for the slag powder sample to analyze the surface morphology of the slag particles and its elemental mapping.

2.4. Toxicity assessment

2.4.1. Acid neutralization capacity test. The leaching test of acid neutralization capacity (ANC) can be performed to obtain the amount of acid required to change the pH of the solution to reach the desired level. To perform this test, 100 ml of distilled water was added to 1 gr of slag powder, and then different volumes of 1 N nitric acid were added. Then, all the Erlene's were placed on a shaker at room temperature until the pH of each sample became constant. Finally, the pH of the samples was measured, and the titration curve was drawn according to the measured pH against the protons consumed per gram of slag powder.[26]

2.4.2. TCLP, SPLP, and WET tests. The TCLP test was conducted to simulate the conditions of the slag landfill and the leaching behavior of the pollutants in the slag, by the method 1311 of the USEPA-SW846 organization.[23] The method of conducting the test is that first the slag sample was mixed with the extracting agent which consisted of 5.7 ml of acetic acid + 64.3 ml of 1 N NaOH, then distilled water was added to it to reach a volume of 1 L and the pH of the solution reached 4.93 ± 0.05. In the next step, the slag was mixed with the extraction agent prepared at a ratio of 1 : 20 and stirred for 18 h at a temperature of 25 °C. Then the prepared mixture was centrifuged and passed through a 0.45 µm filter, and the concentration of metals in the mixture was measured with an ICP-OES device (Spectro Arcos, Spectro Analytical Instruments, Kleve, Germany).

The SPLP leaching test was conducted to evaluate the leaching capability of the slag buried in the landfill according to the 1312 method of the US.EPA. In this test, the slag was mixed with the extraction agent (which includes a mixture of sulfuric acid/nitric acid with a weight percentage of 40 : 60, the pH of the mixture is 4.20 ± 0.05) with a ratio of 1 : 20 and was stirred for 48 h at a temperature of 25 °C.[26]

To perform the WET leaching test, the slag sample was mixed with the extraction agent (which includes 0.2 M sodium citrate adjusted with sodium hydroxide at a pH of 5 ± 0.1) with a ratio of 1 : 10, and then the obtained mixture was stirred for 48 h at a temperature of 25 °C. Then the mixture was centrifuged and filtered, and the concentration of metals in the remaining mixture was measured by ICP-OES.[25]

3. Results and discussion

3.1. Quantification of elemental content of EAF steel slags

The chemical composition of EAF steel slag is shown in the Table 1. According to ICP-OES results, 62.03 wt% of EAF steel slag consists of 42 elements. As the results showed, the concentration of critical elements in the slag sample was Ti > V > Li, respectively, and other critical elements such as Bi, Ga, Sb, In, Sc, and Sr were present in small amounts in the EAF steel slag sample.

Also, various strategic elements such as Fe, Zn, Ag, Cd, Cu, and Sn were observed in the EAF steel slag sample. On the other hand, iron metal (Fe) with a concentration of 144 000 mg kg^{-1}, and then aluminum metal (Al) with a value of 17 600 mg kg^{-1} were the highest concentrations of EAF steel slag constituent metals. The analysis performed on EAF steel slag in Taiwan also showed that Fe is the main component of the slag sample.[18] In another study on EAF slag, it was observed that the slag contains some iron oxide, which is formed due to iron oxidation when oxygen is injected.[6] Also, in the study of Liu and Bao (2024) on EAF slag in China, it is mentioned that the main components of slag include MgO, MnO, CaO, Fe_xO, and SiO_2, and Fe is the largest amount of slag composition.[15]

Studies conducted on the chemical composition of EAF slag in Egypt also showed that this slag contains the main metal oxides Fe_2O_3, Al_2O_3, CaO, SiO_2, and MgO, as well as minor metal oxides including TiO_2, Cr_2O_3, V_2O_5, P_2O_5, K_2O, and MnO. In this study, it is also mentioned that the variation in the chemical composition of slag is related to the technological processes of steelmaking, steel grades, and furnace refractory materials.[12]

Also, alkaline earth metals such as Mg (88 700 mg kg^{-1}) and Ca (177 000 mg kg^{-1}) are observed in large quantities in EAF steel slag, which can be the reason for the alkaline properties of EAF steel slag.

The concentration of toxic metals such as Pb, Sn, Cr, Cd, and As in EAF steel slag was 800, 10, 10, 10, 10, and 10 mg kg^{-1}, respectively. The concentration of these metals was less than 1000 mg kg^{-1}. Considering that these metals are very toxic, if they are released into the environment, they can endanger the health of humans and animals.[25] Considering that the ICP-OES results in Table 1 showed that the concentration of Pb, Sn, Cr, Cd, and As metals in the EAF steel slag sample is low, therefore EAF steel slag is not a high risk for the environment.[27,28] Menad *et al.* (2021) reported that the concentrations of Pb, Zn, Ni, and Cu metals in EAF slag in France were 23, 677, 743, and 10 mg kg^{-1}, respectively. In this study, it is mentioned that slag is classified as non-hazardous.[29]

There was 5700 mg kg^{-1} of Si in the EAF steel slag sample, which is also observed in the XRD analysis of silica-containing compounds.

3.2. Initial pH of EAF steel slags

The initial pH of the EAF slag sample in distilled water was 10.9 after 24 h. The reason for the alkalinity of the EAF slag sample is due to the presence of alkali metal and alkaline earth in the slag, which causes the high alkalinity of the slag, so that the slag has a high capacity to neutralize strong acidic solutions.[8]

EAF slag is alkaline due to the presence of calcium oxides in it. When slag is exposed to a water source, an ionic matrix of Ca–CO_3–OH is formed, which shows a pH of about 10 to 12.5. For this reason, EAF slag is used to drain acid mines and increase soil pH.[6]

In the examined samples of EAF slag from two steel companies in Colombia, the results showed that these slags have alkaline properties and the pH of two slag samples was reported as 11.80 and 11.78, which is consistent with the present study. The reason for the alkalinity of EAF slag was mainly due to the high content of CaO in the samples. Thus, EAF slags are a source of metal cations that exist in the form of metal oxides in the slag structure.[30]

Table 1 Metal content of EAF steel slags by ICP-OES

Elements	Concentration (mg kg^{-1})	Elements	Concentration (mg kg^{-1})	Elements	Concentration (mg kg^{-1})
Ca	177 000	Ba	520	Cd	10
Fe	144 000	Li	280	Sn	10
K	123 000	Au	24	P	10
Al	17 600	As	10	B	10
Mg	88 700	Ag	10	In	10
Zn	3600	Cr	10	Sb	10
Ti	3600	Co	10	Ga	10
Si	5700	Cu	10	Pr	10
V	2400	Sr	10	Ce	10
Mn	1400	Sc	10	La	10
Pb	800	Y	10	Hg	9

The pH measurement results of two EAF slag samples in Italy showed that the pH values of the samples were equal to 11.3 and 10.8, which indicates the alkaline nature of EAF slag.[31]

3.3. Analyses of EAF steel slags structural phases and functional groups evaluation

3.3.1. XRD spectrum. XRD analysis was done to determine the chemical composition of EAF steel slag and the results are presented in Fig. 1. As seen in Fig. 1, the crystal structure of steel slag has multiple peaks in the range of 25° to 80° in the XRD spectrum, which is attributed to crystalline phases with sharp peaks and several shorter peaks. In general, as can be seen, the composition of slag consists of iron oxides and silicates. The main constituent phases in steel slag as shown in XRD analysis include Fe, $(MgO)_{0.77}$ $(FeO)_{0.23}$, Fe_3O_4, $(Fe_{0.32}Si_{0.67})$ $(Fe_{0.96}Si_{0.03})_2O_4$, $CaSiO_3$, $Ca_4Fe_{14}O_{25}$, $Ca_4Fe_9O_{17}$, $CaMgSiO_4$, and Fe_2O_3.

Studies have shown that the chemical composition and mineral components of EAF slag are different depending on the raw materials entering the furnace, the purification process, and the cooling process.[4]

Based on the studies of Chiang and Pan (2017), the crystalline phases in EAF slag were divided into different phases including silicates (such as gehlenite, bregedite, and larnite), iron oxides (such as hematite, magnetite, wustite) and manganese oxides (such as groutellite, hausmannite, birnessite).[32]

Also, in the study conducted on Columbia slags, it was observed that iron oxides are mainly magnetite (Fe_3O_4) and wustite (FeO) in EAF slag samples, and the amount of free magnesium and lime in these slags is insignificant.[30]

Peaks 23.5°, 43.7°, and 62.7° indicate the presence of Fe in the steel slag sample, which was also observed in the ICP-OES elemental analysis results that Fe is the dominant element in EAF steel slag.

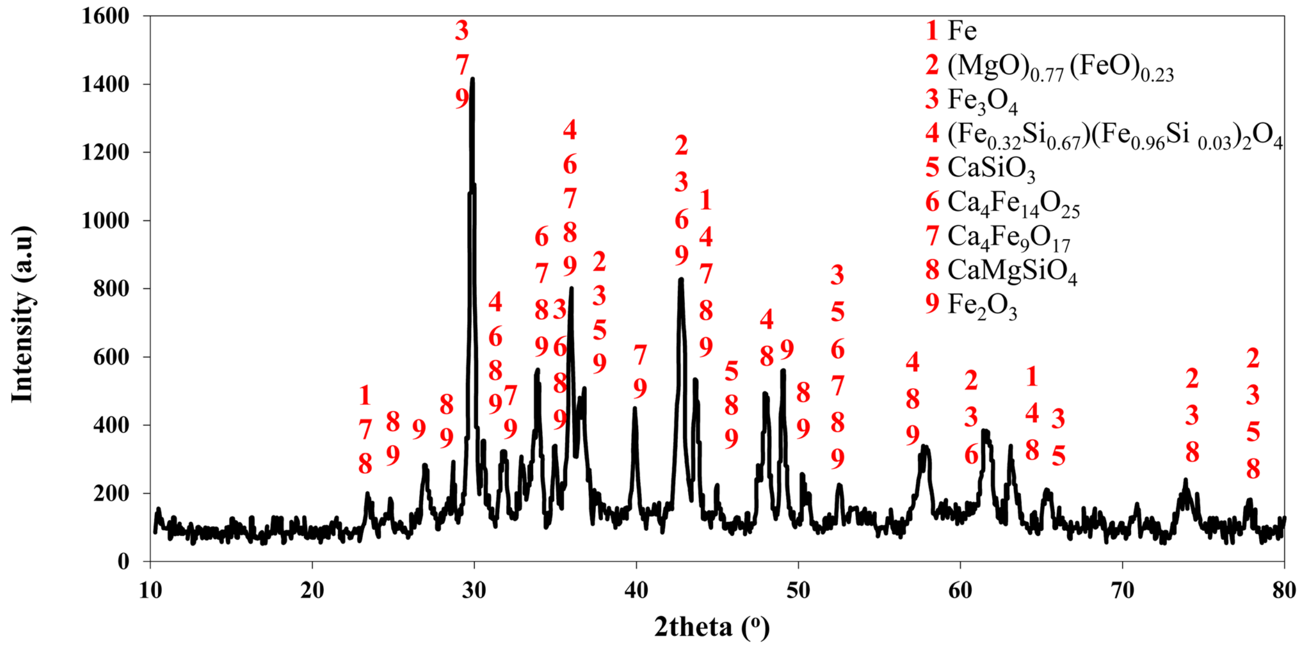


Fig. 1 XRD pattern of EAF steel slags.

Also, other mineral phases containing iron such as magnetite (Fe_3O_4) and hematite (Fe_2O_3) were observed in different peaks of the XRD pattern of EAF steel slag. Thus, Fe_3O_4 was observed in peaks 29.9°, 35°, 36.7°, 42.8°, 52.6°, 61.8°, 74° and 78.2°.

Fe_2O_3 was also observed in sharp peaks 29.9°, 30.6, 33.8°, 36°, 36.8°, 39.9°, 42.8°, 43.7°, 49.1°, 52.6° and 57.8°. In the investigations of Hocheng *et al.* (2014), various mineral phases such as wustite (FeO), magnetite (Fe_3O_4), portland ($Ca(OH)_2$), hematite (Fe_2O_3), calcite ($CaCO_3$) and lime (CaO) were observed in the XRD pattern of the EAF steel slag sample.[18]

Other mineral compounds containing calcium, silica, and magnesium are also observed in the EAF steel slag sample. The results of the present study are consistent with the study of Zulkifili (2022) as it was also observed in this study that calcium (Ca), iron (Fe), silica (Si), manganese (Mn), and aluminum (Al) are present in Penang steel slag and iron, silicon, and calcium oxides made up about 75% of the chemical composition of slag.[33]

Also, in the study of Teo *et al.* (2020), it was observed that the main elements in EAF slags are aluminum, calcium, iron, and silicon oxides, and manganese and magnesium oxides are also observed in these slags.[6] In another research conducted in Montenegro on EAF slag, it was also observed that the main crystalline phases in XRD analysis include 40% larnite and 20% wustite, and a small amount of gehlenite was also observed.[3]

The results of the study conducted on EAF slag in China also showed that the main phases of slag based on XRD analysis results include Fe_3O_4, Ca_2SiO_4, $MnFe_2O_4$, $MgFe_2O_4$, and $Ca_2Fe_2O_5$, which is consistent with the present study.[15]

The change in the XRD phases of the slag sample in the present study compared to other previous studies can be related to the controlling parameters of steelmaking.[12]

3.3.2. FTIR studies. To identify the functional groups in the structure of EAF steel slag, FTIR spectroscopic analysis was performed and the results of FTIR spectrum are shown in Fig. 2.

The small peak at 476.82 cm^{-1} corresponds to the Si–O bending vibration. The absorption peak at the wavelength of 519.41 cm^{-1} is related to O–Si–O bending vibration.[4]

The absorption spectra at 712.40 and 873.43 cm^{-1} respectively show the in-plane bending vibrations and out-of-plane bending vibrations of CO_3^{2-} in calcite.[4]

The band of 1010.60 cm^{-1} corresponds to the stretching and bending bands of SI–O, which indicates the presence of silicates in EAF slag, which was also observed in the study of Balaguera and Botero.[30]

Peaks 1422.34 and 1797.87 correspond to the stretching states of C–O functional groups in CO_3^{2-} ions.[8]

The peak at 3428.86 cm^{-1} is related to O–H functional groups, which are driven by interlayer water and water adsorbed in EAF slag.[4]

3.4. Surface morphology of EAF steel slags

The FE-SEM image of the EAF slag sample shows that the slag has a rough surface texture with different particle sizes, which is consistent with the study by Teo *et al.* (2020) (Fig. 3(A)).[6] Generally, particles with irregular shapes due to the crushing and grinding process of the EAF slag sample are observed in Fig. 3(C). As the results show, EAF slag is a complex heterogeneous material.[12] In the investigated samples of EAF slag in Colombia, particles with irregular and angular structures were observed, which is consistent with the present study.[30] Also, the EAF slag sample in the present study had a gray color.

The remarkable thing about EAF slag is that the physical properties of this slag vary depending on the composition of the input feed to the furnace, the refining processes, the type of furnace, and the grade of steel produced.[6]

EDX results of EAF steel slag in this study showed that it contains elements of O (34.06 wt%), Ca (25.07 wt%), Si (13.35 wt%), Fe (9.10 wt%), Mg (6.28 wt%), Al (4.27 wt%) and C (3.63 wt%) (Fig. 3(B)). Also, other elements, including Ti, P, and Na, were observed in small amounts in the slag.

Considering that in steel electric arc furnaces, oxygen is used to oxidize impurities and also to purify steel, so probably the reason for the high amount of oxygen in the EAF slag in the present study is the blowing of oxygen into the furnace.[11]

In the EDX results on the EAF slag from the Shandong Laiwu Steel Plant, the presence of Fe, Si, Al, Mg, and P elements was also determined.[4] Also, in the study of Balaguera *et al.* (2020), the EDX results of EAF slag showed that the most elements in the slag were Si, Fe, O, and Ca.[30] The results observed on slag samples in Egypt also showed the presence of Fe, Si, O, Na, Ca, Mg, V, Ti, Cr, P, Al, and K elements. Also, elements with the highest weight percentage included Fe (37.1 wt%), Ca (24.64 wt%), Fe (17.55 wt%), and Al (6.11 wt%).[12] The presence of phosphorus element in the slag is due to the origin of the input feed to electric arc furnaces, which usually originates from scraps that are made of alloy metals.[30]

Elemental mapping of the EAF slag sample showed the presence of Al, Fe, Si, Mg, Ti, P, Ca, and Na elements in the slag, which is consistent with the ICP-OES and XRD results (Fig. 3(C)).

3.5. Toxicity assessments

3.5.1. ANC test. The acid neutralization capacity test determines the alkalinity and buffering capacity of a system.[34,35] The higher ANC of EAF slag means that more acid should be used to reduce the pH of the solution.[36] The ANC of the EAF steel slag sample is shown in Fig. 4. The findings of this study demonstrated that a pH of 6 could be achieved by adding 10 mmol H^+/gr EAF steel slag. Furthermore, adding 6.8 mmol H^+/gr EAF steel slag resulted in a final pH value of 4 for the EAF steel slag sample. It can be generally concluded that the pH of the slag decreases with the addition of a significant quantity of acid and that the neutralization capacity of the waste acid is considerable.

Baek *et al.* (2021) reported that mixed slag (70% steel slag + 30% blast furnace slag) has a high acid neutralization capacity against acidic rocks in the Pohang region. So that about 0.161 g of mixed slag is required to neutralize each of the acidic rock samples to pH 7. This strong neutralization performance was primarily attributed to the high CaO content of the mixed slag,

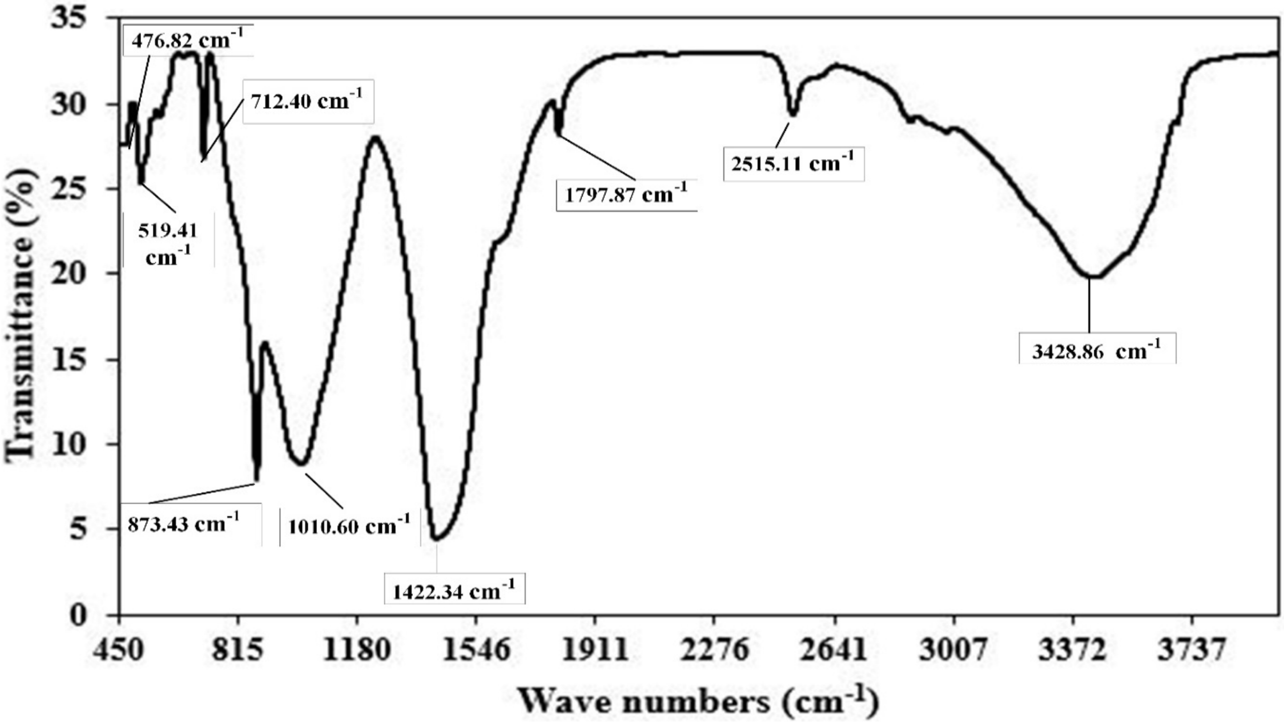


Fig. 2 FTIR spectra data of EAF steel slags.

highlighting its potential effectiveness as an acid-neutralizing agent.[37] In a similar study conducted by Yang *et al.* (2022) on the determination of the acid neutralization capacity of basic oxygen furnace steel slag on acidic mine drainage in China, the results showed that the ANC value of slag to reach pH = 7 on acidic mine drainage was 8 mmol H^+/g slag. The neutralization mechanism was attributed to the reaction of alkaline slag constituents, including MgO, C_2S, $CaO \cdot Fe_2O_3$, and free CaO (f-CaO), which are present on the surface of slag particles and interact with acidic mine drainage, thereby facilitating pH neutralization.[38]

3.5.2. EAF steel slags analysis using TCLP, SPLP, and WET. Leaching tests (TCLP, SPLP, and WET) are used to investigate the mobility of metals in wastes such as slags and to predict the long-term environmental behavior of slags.[28] The results of TCLP, SPLP, and WET tests related to the EAF steel slag sample with the permissible threshold limit of metals based on the guidelines of the United States Environmental Protection Agency (US.EPA) and the California Department of Toxic Substances Control (CDTSC) are shown in Table 2.

Investigating the slag leaching behavior is to measure the amount and concentration of metals released when the slag is placed in the washing sources. This review is done to identify whether the slag is environmentally friendly, safe, and non-hazardous. Leaching tests evaluate the concentrations of toxic heavy metals leached from slag samples and compare them to regulations reported by the EPA.[6] In addition, the results of leaching tests influence the choice of how slag is treated, how slag is disposed of, and how slag is used in environmental applications or as a resource for construction.[28]

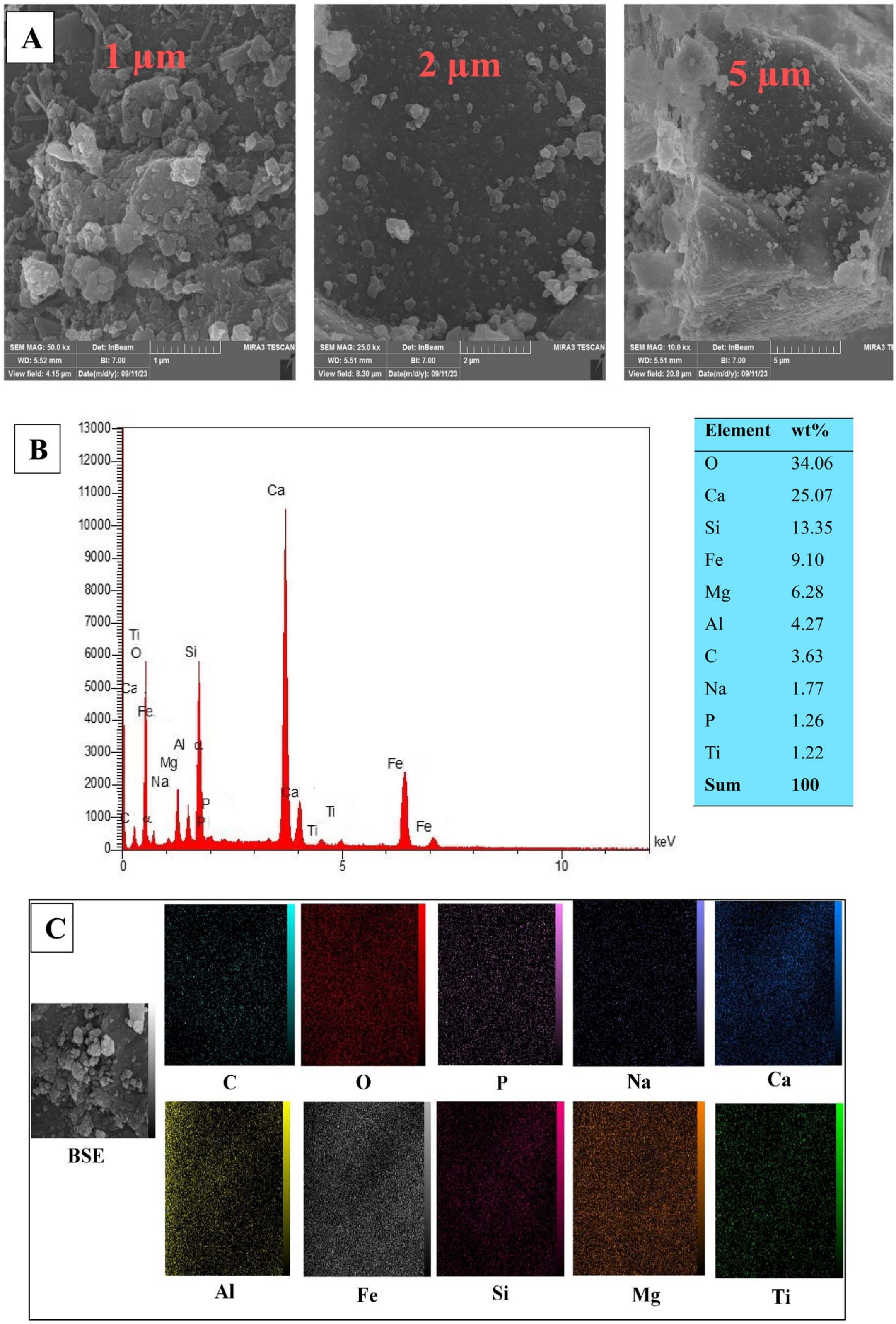
The results of TCLP, SPLP, and WET tests on the EAF steel slag sample in the present study showed that the concentration of Ba, Mn, Pb, Si, Ti, Al, Fe, V, Mg, and Zn metals is within the permissible limits of EPA and CDTSC standards (Table 2). Therefore, slag is not considered hazardous and toxic waste and is safe for environmental disposal.

The results of the TCLP leaching test on two EAF slags in the Italian steel industry showed that both slags are classified as non-hazardous and special non-toxic waste, and the washing of heavy metals from these two types of slags is within the limits of Italian standards.[31]

In the study of Singh *et al.* (2021) on EAF slag, the TCLP leaching test was conducted at pH 4.93 and 2.88, the results showed that the leaching of hazardous heavy metals in the EAF slag sample is negligible and is within the permissible range of the EPA standard.[39] The important point is that even if EAF slags are not considered hazardous materials, from an environmental point of view considering that millions of tons of slags have been stored in landfills for a long time, it is necessary to investigate the environmental effects related to their disposal for security reasons.[8]

3.6. Environmental implications and mitigation strategies for EAF slag

The results of comprehensive characterization and leaching behavior of the EAF slag investigated in this study indicate that it poses little environmental risk under typical disposal and exposure conditions. The alkaline nature of EAF slag and its high acid neutralization capacity indicate a strong buffering behavior of the slag, which, if not properly managed, may affect the chemistry of



Element	wt%
O	34.06
Ca	25.07
Si	13.35
Fe	9.10
Mg	6.28
Al	4.27
C	3.63
Na	1.77
P	1.26
Ti	1.22
Sum	**100**

Fig. 3 (A) FE-SEM analysis of EAF steel; (B) EDX analysis; (C) BSE image and elemental image mapping slag.

surrounding soil and water. However, the results of the TCLP, SPLP, and WET tests indicate that the release of potentially hazardous metals is still below regulatory thresholds, classifying the slag as non-hazardous according to EPA criteria. These findings indicate that under controlled conditions, EAF slag is unlikely to cause significant groundwater or soil contamination.

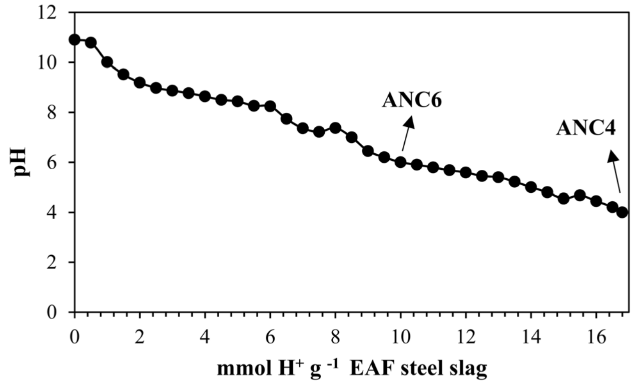


Fig. 4 ANC of EAF steel slags.

Table 2 EAF steel slags (mg L^{-1}) leaching test using TCLP, SPLP, and WET[a]

Metal	TCLP	TCLP limit	SPLP	SPLP limit	WET	WET limit
Ba	0.15	100	<0.01	100	0.19	100
Mn	0.41	n.s	<0.01	n.s	3.42	n.s
Pb	0.24	5	<0.01	5	<0.01	5
Si	22.5	n.s	1.41	n.s	14.3	n.s
Ti	0.10	n.s	<0.01	n.s	0.15	n.s
Al	<0.01	n.s	<0.01	n.s	3.26	n.s
Fe	46.5	n.s	30.4	n.s	1.71	n.s
V	<0.01	n.s	<0.01	n.s	<0.01	24
Mg	3.94	n.s	6.27	n.s	34.9	n.s
Zn	<0.01	n.s	<0.01	n.s	0.61	250

[a] n.s.: not stated.

Therefore, to mitigation the potential environmental impacts of EAF slag, various strategies can be used, such as controlled use of slag in construction materials,[40] road construction,[41] as an acid-neutralizing agent[28] or soil stabilization,[42] which bring economic and environmental benefits. Furthermore, due to the presence of various metals in slag, selective recovery or processing can be considered in cases where it is economically feasible. Also, in cases where slag disposal is required, engineered landfill systems with proper drainage and containment are recommended to prevent adverse interactions with groundwater and surrounding soil. Overall, the findings of this study provide a scientific basis for selecting environmentally friendly and cost-effective management strategies for EAF steel slag.

4. Conclusion

The rapid growth of global steel production has led to the generation of substantial quantities of EAF slag, underscoring the need for its effective management and recycling. This study provided a comprehensive evaluation of the physicochemical, morphological, and leaching behavior of EAF slag. The results demonstrated that EAF slag contains significant concentrations of various metals, with Fe (144 000 mg kg^{-1}) as the dominant component, followed by Al (17 600 mg kg^{-1}), Si (5700 mg kg^{-1}), Ti (3600 mg kg^{-1}), Zn (3600 mg kg^{-1}), and V (2400 mg kg^{-1}). The high contents of alkaline elements such as Ca, Mg, and K imparted strong alkalinity (pH ≈ 10), indicating potential applicability in neutralizing acidic soils and aqueous environments. XRD analyses indicated that the slag comprises multiple crystalline phases predominantly composed of iron, calcium, and silica oxides. Spectroscopic results further confirmed the presence of diverse functional groups, while FE-SEM observations revealed a heterogeneous surface morphology with variable particle sizes. EDX-mapping confirmed the distribution of major elements, including Fe, Si, Ti, Ca, and Al. Acid neutralization capacity testing showed a high buffering potential, and standardized leaching tests (TCLP, SPLP, and WET) confirmed that metals release levels were within regulatory limits, classifying the slag as non-hazardous. Overall, the findings provide a sound scientific basis for informed decision-making regarding the sustainable management, reuse, and environmental safety of EAF steel slag.

Author's contribution

Zoha Heidarinejad: investigation, methodology, writing – original draft, data curation, conceptualization. Mahdi Farzadkia: supervision, writing – review & editing, project administration, methodology. Seyyed Mohammad Mousavi: supervision, resources, project administration, conceptualization, methodology.

Conflicts of interest

The authors declare that they have no known financial conflicts of interest or personal associations that could be perceived as influencing the research presented in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the Student Research Committee, Iran University of Medical Sciences, under grant number 1403-2-15-31132. The authors extend their sincere appreciation to the Student Research Committee, Iran University of Medical Sciences, for their support of this research. This research received approval from the Research Ethics Committees of the Iran University of Medical Sciences (IR.IUMS.REC.1403.767).

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