

SUSTAINABLE APPROACHES FOR LD SLAG WASTE MANAGEMENT IN STEEL INDUSTRIES: A REVIEW

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Reduce, reuse, and recycle are important techniques for waste management. These become significant for improving environmental and economic condition of industries. Integrated steel industries are generating huge amounts of steel slag as waste through the blast furnace and Linz–Donawitz (LD) process. Presently, these wastes are disposed by dumping in an unplanned manner, which causes many environmental problems. The generation rate of slag produced from steel industries is found to be in the range of 150–200 kg per ton of steel production. The LD slag generated by the basic oxygen converter is one of the waste which can be reused due to the presence of a considerable amount of valuable minerals. In order to recycle and reuse the waste, assessment of their physicochemical, mineralogical and geotechnical characterization is imperative. This paper addresses the characterization and possible utilization of LD slag.

Keywords: steel, LD slag, characterization, recycle, utilization, waste management.

Introduction. Steel production in all integrated steel plants requires five components, namely air, water, fuel, power, and raw materials like iron ore, limestone, etc. During the steel production process, considerable amounts of solid wastes are being generated in steelmaking units such as blast furnace (BF) slag, tar sludge, flue dust, Linz–Donawitz (LD) converter slag, etc. The basic oxygen furnace (BOF) steelmaking slag, also known as LD slag, is one of the important industrial byproducts generated in the steelmaking process or pig iron refining process from integrated steel plants. In this process, the hot metal is converted to steel by blowing of oxygen in the LD converters [1–4]. The LD slag contains a considerable amount of metals and chemical components that can be useful for various applications. The chemical composition and major phases of typical LD slag samples generated at integrated steel plants in India [1] are depicted in Table 1.

The average rate of generation of LD slag is approximately 150–180 kg per ton of crude steel in India [5]. Researchers also found that this rate of production of LD slag sometimes reaches a high of 200 kg per ton of crude steel [6]. In India, over 12.15–14.58 metric tons of steelmelting slag has been generated in the financial year 2013, and this rate is still increasing with the escalation of steel production [7]. However, it depends on the quality of raw materials and yield efficiency of the steel plants. In India, the utilization of LD slag is a meager 25% compared to a high of 70–100% in other countries [6]. Therefore, disposal of this huge mass of waste slag has become a problem due to environmental and space constraints in the steel plants. The utilization of integrated steel plant waste by an economical and environmental friendly technique will decrease a major portion of the production cost. If these steel plant wastes are reused as a raw material substitute, then it is possible to conserve valuable natural resources like dolomite that are used as fluxing material to reduce the iron in steelmaking and thereby reduce the environmental hazards of mining the ore and reduce slag dumping space [8]. Special processing of slag can produce similar aggregate products originating from the rock and mineral industries. Therefore, much effort has been exerted on utilization

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TABLE 1. Chemical Composition and Major Phases of Typical LD Slag Generated at Integrated Steel Plants in India

Chemical composition	Major phases	wt.%
SiO ₂ – 12.16%	Tricalcium silicate (C ₃ S), Ca ₃ SiO ₅	0–20%
Al ₂ O ₃ – 1.22%	Dicalcium silicate (C ₂ S), Ca ₂ SiO ₄	30–60%
FeO – 26.30%	Other silicates	0–10%
CaO – 47.88%	Magnesiocalciowustite	15–30%
MnO – 0.28%	Dicalcium aluminoferrite (Ca ₂ (Fe, Al, Ti) ₂ O ₅)	10–25%
MgO – 0.82%	Magnesium type phase (Fe, Mn, Mg, Ca)O	0–5%
P ₂ O ₅ – 3.33%	Lime phase (Ca, Fe)O	0–15%
S – 0.28%	Periclase (Mg, Fe)O	0–5%
Na ₂ O – 0.036%	Fluorite CaF ₂	0–1%
K ₂ O – 0.071%	–	–

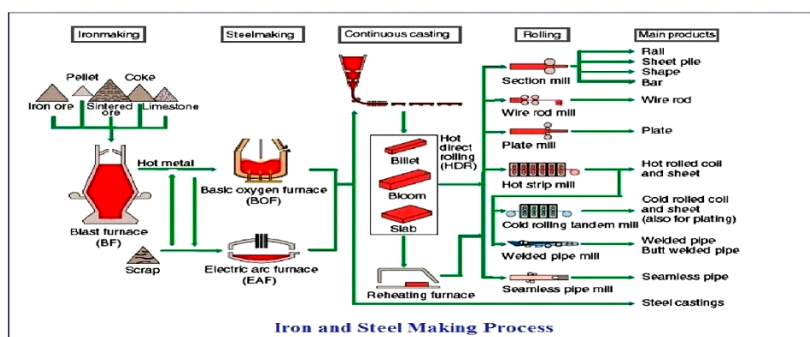


Fig. 1. Flowchart of iron and steelmaking processes and slag generation in modern steel plant, modified from [12].

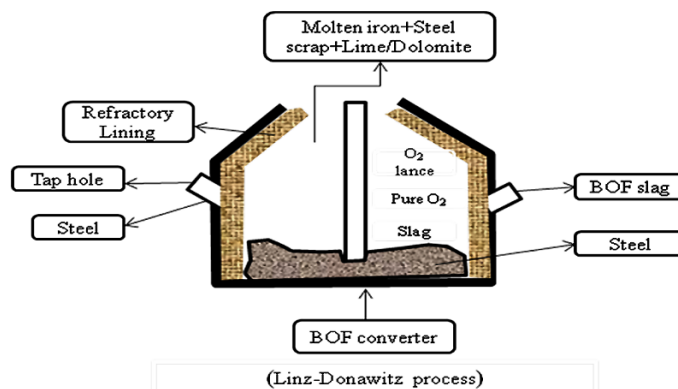


Fig. 2. Schematic representation of the basic oxygen furnace process, modified from [12].

of slags as raw materials for infrastructure sector. The LD slag is utilized as a raw material for concrete production, road construction, railway ballast, plastering, and other civil engineering works [9]. Such utilization of the slags will bring in the 3R (reduce, reuse, and recycle) concept to provide an effective and sustainable disposal system for this industrial waste.

TABLE 2. Chemical Composition of LD/BOF Steel Slag

Sr. No.	Slag type	Oxides composition in (%)											References	
		CaO	MnO	MgO	FeO	SiO ₂	Fe ₂ O ₃	Fe _{tot}	SO ₃	TiO ₂	P ₂ O ₅	Al ₂ O ₃		Free CaO
1	LD/BOF	35	6.5	11.5	25	18	–	–	–	–	–	3.5	–	[16]**
2	LD/BOF	56	2.5	1.7	21	10	–	–	0.2	3.1	–	2.0	–	[17]
3	LD/BOF	45–60	–	3–13	7–20	10–15	3–9	–	–	–	1–4	1–5	–	[18]
4	LD/BOF	45–52	4–7	4–5	5–20	13–16	1–8	–	0.1–0.2	0.4–0.9	1.6–2.1	0.9–1.7	–	[19]
5	LD/BOF	42–45	<5	3–8	14–20	12–18	–	–	–	–	<2.0	<3.0	<10	[20]
6	LD/BOF	40–50	4–9	5–15	10–35	10–20	–	–	–	–	–	1–7	–	[21]
7	LD/BOF	37–38	7.5–8.0	14.0	11–14	18–19	–	–	–	–	–	2.5–3	–	[22]*
8	LD/BOF	41.9	5.8	5.2	11.7	26.6	–	–	–	–	–	3.2	–	[23]
9	LD/BOF	36.4–45.8	2.7–4.3	4.1–7.8	–	10.7–15.2	–	19–24	0.1–0.2	–	1–1.5	1–3.4	2.5–12	[24]
10	LD/BOF	45–55	<5	<3	14–20	12–18	–	–	–	–	<2	<3	–	[25]
11	LD/BOF	31–35	5–8	7.5–9.0	25–30	17–22	–	–	–	–	–	2.5–4.5	–	[26]
12	LD/BOF	30–55	2–8	5–15	10–35	8–20	–	–	0.1–0.2	0.4–2	0.2–2	1–6	–	[27]
13	LD/BOF	52.2	2.5	5.04	17.2	10.8	10.1	–	–	0.6	1.3	1.3	10.2	[28]
14	LD/BOF	47.88	0.28	0.82	26.30	12.16	–	–	0.28	–	3.33	1.22	–	[1]
15	LD/BOF	45.0	3.1	9.6	10.7	11.1	10.9	–	–	–	–	1.9	–	[29]
16	LD/BOF	47.5	1.9	6.3	–	11.8	22.6	–	–	0.5	2.7	2.0	–	[30]
17	LD/BOF	39.3	4.2	8.56	–	7.8	38.06	–	0.0	0.9	–	0.98	–	[4]
18	LD/BOF	47.71	2.64	6.4	–	13.3	24.36	–	–	0.7	1.5	3.04	9.2	[14]
19	LD/BOF	52.7	3.0	6.1	20.6	12.6	–	–	–	–	–	1.4	–	[31]
20	LD/BOF	44.29	4.52	0.89	–	6.88	17.57	–	0.79	0.98	1.91	1.24	–	[32]
21	LD/BOF	53.24	0.28	1.4	21.6	9.88	–	–	–	–	1.73	1.39	–	[33]
22	LD/BOF	42.3	2.32	6.88	24.59	10.78	–	–	–	–	–	1.18	–	[34]
23	LD/BOF	45.41	0.84	8.17	24.05	14.05	–	–	0.24	0.76	1.53	4.34	–	[35]
24	LD/BOF	52.7	3.0	6.1	20.6	12.6	–	–	0.04	0.6	2.7	1.4	–	[36]

* The range of values is compiled based on the chemical composition data from four different sources in Great Britain provided by [22].
 ** Reference [16] reports the chemical composition of steel slag from the refining process (not specified as BOF).
 – Data not available.

Steelmaking process by basic oxygen furnace (BOF) or Linz–Donawitz (LD) converter and slag generation: In all integrated steel plants, basic oxygen furnaces are charged with the molten iron produced in the blast furnace along with steel scraps. Usually, the BOF charge consists mainly of about 10–20% of steel scrap and 80–90% of molten iron [10–11]. A typical iron and steelmaking process is depicted in (Fig. 1) [12]. The BOF/LD has to be maintained at a temperature of approximately 1600–1650°C. Figure 2 shows a schematic diagram of the BOF process and its slag generation.

TABLE 3. Composition of Several Phases in LD Slag

No:	Slag type	Mineral phases	References
1	LD/BOF	C_3S , C_2S , C_2F , RO phase (FeO–MgO–CaO–FeO), MgO, CaO	[24]
2	LD/BOF	$2CaO \cdot Al_2O_3 \cdot SiO_2$, Fe_2O_3 , CaO, FeO	[37]
3	LD/BOF	$2CaO \cdot Fe_2O_3$, $2CaO \cdot P_2O_5$, $2CaO \cdot SiO_2$, CaO	[38]
4	LD/BOF	$2CaO \cdot Fe_2O_3$, $3CaO \cdot SiO_2$, $2CaO \cdot SiO_2$, Fe_2O_3	[38]
5	LD/BOF	β - Ca_2SiO_4 , FeO–MnO–MgO solid solution, MgO	[29]
6	LD/BOF	Ca_2SiO_4 , Ca_3SiO_5 , FeO, $2CaO \cdot Fe_2O_3$	[39]
7	LD/BOF	(C_3S), Ca_3SiO_5 , (C_2S), Ca_2SiO_4 , (Fe, Mn, Mg, Ca)O, other silicates, magnesiocalciowustite, CaF_2 , $(Ca_2(Fe, Al, Ti)_2O_5)$	[15]

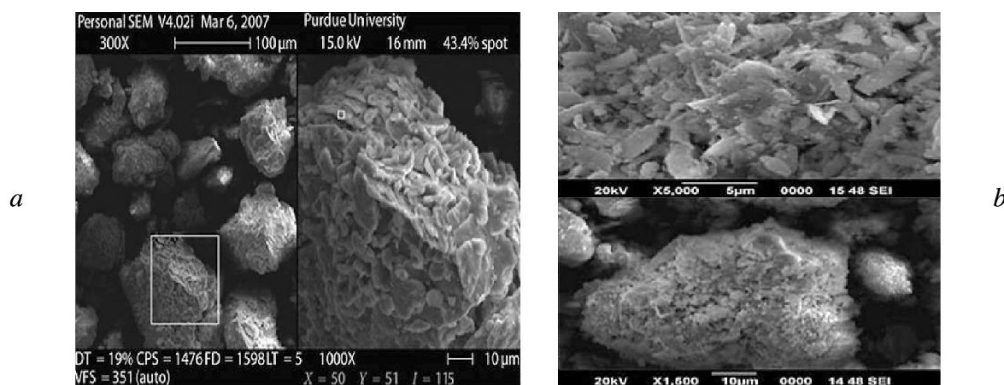


Fig. 3. SEM micrographs of LD slag samples: *a*) LD slag from Mittal Steel, Indiana Harbor Works West Plant, Indiana. Image shows that the sand and silt size LD slag particles are subrounded to angular shapes [12]; *b*) LD slag from Bokaro Steel Plant, Jharkhand, India. Image shows that LD slag particles are rough textured, cubical and angular in external appearance and internally vesicular in nature [35].

Initially in BOF, the steel scrap is charged and a ladle of molten iron (~200 tons) is poured over it with a crane. An oxygen lance is then lowered into the furnace, which blows 99% pure oxygen on the charge at supersonic speed. The blowing cycle continues for 20–25 min, wherein intense oxidation reaction removes the impurities of the charge. The carbon impregnated in the steel is burnt to form carbon monoxide, causing the temperature to rise to 1600–1700°C. The scrap gets melted and the carbon content of the molten iron is lowered [10–11]. The furnace is also charged with fluxing agents, such as lime (CaO) or dolomite ($MgCa(CO_3)_2$), to remove the unwanted chemical elements of the melt during the oxygen blowing cycles. Molten metal samples are collected and tested for their chemical composition near the end of the blowing cycle. Once the chemical composition is achieved, the oxygen lance is pulled up from the furnace. The BOF is then tilted in one direction in order to tap the steel into ladles. The steel produced either undergoes further refining in a secondary refining unit or sent directly to a continuous caster where semifinished shapes are solidified. After the molten steel is removed from the BOF, it is again tilted in the opposite direction to pour the liquid slag into ladles. From the steelmaking cycle, the slag is later processed, and the final product is referred to as LD slag [10, 11, 13].

Chemical and mineralogical composition of LD slag. The chemical and mineralogical characteristics of LD slag are determined mainly by using the ICP-AES and C-H-N-S analyzer, and the main mineral phases by using x-ray diffraction (XRD), scanning electron microscope (SEM), electron probe microanalysis (EPMA), and energy dispersive x-ray spectroscopy (EDS). It was observed that the slag contains mainly various components like CaO, Fe, SiO_2 , and Mn. The lime content

TABLE 4. Geotechnical Properties of LD Slag

Properties	LD slag	Basalt	Granite
Bulk density (g/cm^3)	3.1–3.7	2.8–3.1	2.6–2.8
Resistance to impact determined on crushed aggregates (8–12 mm) (%)	10–26	9–20	12–27
Absorption of water (%)	0.2–0.1	<0.5	0.3–1.2
Freeze/thaw resistance (<5 mm) (%)	<1	<1.0	0.8–2.0
Los Angeles test (test aggregates: 8–12 mm) (%)	9–18	–	15–20
Polished stone value (PSV)	54–57	45–55	45–55
Compressive strength (N/mm^2)	>100	>250	>120

measurements were carried out by using three different analytical techniques, namely the Leduc test, thermos-gravimetric analysis, and Bernard calcinatory analysis [14]. The major phases present in LD slag were studied and found to contain two phases, one that contains some reactive mineral phases such as $2\text{CaO}\cdot\text{SiO}_2$, $3\text{CaO}\cdot\text{SiO}_2$, and free CaO and MgO, while the other is the metal phase [15]. The EPMA study of LD slag sample was carried out to determine the association of phosphorus in LD slag, and there was some variation found with respect to Fe, Ca, Al, and Mn content. However, it is evident that the P content in the slag is more attached to the calcium phase than to the iron phase [1]. The chemical composition and several phases of LD slag are summarized in Tables 2 and 3, respectively.

Morphological properties of LD slag. Different studies have been carried out on the morphological characteristics of LD slag. From SEM studies it is observed that LD slag samples are rough textured, cubical and angular in external appearance. Internally, each particle is vesicular in nature with many noninterconnected cells. The cellular structures are formed by the gases entrapped in the hot slag at the time of cooling and solidification. Since these cells do not form connecting passages, the term cellular or vesicle is more applicable to steel slag than the term porous [35]. Other SEM studies show that the sand and silt size BOF slag particles have subrounded to angular shapes. Distinct asperities and edges are visible in angular, bulky particles. Most of the sand and silt size particles examined under the SEM have rough surface textures as depicted in (Fig. 3) [12, 33].

Geotechnical properties of LD slag. The applications of LD slag samples are closely related to their geotechnical properties. Some of the geotechnical properties of steel slags were investigated and compared with those of natural aggregates [40]. The results are summarized in Table 4. Based on the above geotechnical properties, it can be observed that

- 1) the densities of steel slag are higher than those of the natural aggregates due to the high content of iron;
- 2) steel slags are hard materials, as their compressive strengths are close to the strength of granite; and
- 3) the resistance of steel slags to impact is approximately similar to the natural aggregates as they are difficult to crush, and the Los Angeles test values are also high, indicating that they are difficult to grind.

Additionally, steel slags contain some reactive minerals like $2\text{CaO}\cdot\text{SiO}_2$, $3\text{CaO}\cdot\text{SiO}_2$, and free CaO and MgO, which are water hardenable materials [41, 42]. When certain amounts of free CaO or MgO are present in steel slag, the slag is not stable in volume due to the hydration of these free compounds [40, 42, 43].

Environmental issues of LD slag. It has been noted by some researchers that the discharge of metals and elements from LD slag may cause environmental problems such as air, water, and soil pollution. These dry LD slag dumps represent a toxicological risk to the human body through inhalation of small slag particles i.e., those less than $10\ \mu\text{m}$ [44–49]. The leachates pollute the soil, groundwater, as well as surface water bodies. To confirm this statement, the leaching parameters were studied by conducting toxicity characteristic leaching procedure (TCLP) test of iron and steel slags in the USA. It was observed that the trace elements that may be present include nickel, chromium, lead, zinc, titanium, and vanadium. Chromium is found in higher amounts in the slag, but the concentrations in the leachate are low because the chromium ions are bound within stable crystalline phases. It has been observed that none of the metals in the leachates exceed the TCLP criterion concentrations. LD slag can be highly alkaline due to the presence of free lime. The runoff of leachate through exposed steel slag

stockpiles, embankment fills or granular bases can exhibit high pH values, which may impact the local aquatic ecology. Organic chemicals or substances do not exist in the slag because of their high melting temperatures. The dumping of slags causes a shortage of land and other associated problems. Thus, it can be concluded that iron and steel slags should not be considered a hazardous waste and may be used for various purposes [49].

Utilizations of LD Slag

Use for soil stabilization and as a soil conditioner. LD slag is used as a soil additive to improve its physicochemical properties and in situ stabilization of Cu and other trace metals in a sandy Cu contaminated soil. It was found that soil pH increases with a higher incorporation rate of LD slag and allows bean growth, foliar Ca concentration, and further reduced foliar Cu concentration below its upper critical value, thus avoiding excessive soil EC and Zn deficiency [50]. Experiments have found that the soil pH increases from 5.3 to 6.4 with the use of 7500 kg of slag per hectare, the second year response being higher, i.e., 41% increase in the soil pH with 3000 kg slag per hectare [51]. This is in the natural range and shows a positive effect on mustard and wheat seedling growth. Thus, this can be used in rural agriculture for better plant growth [52]. The Government of India, Ministry of Finance, has issued a circular (Circular No 553/49/2000-CX New Delhi, October 18, 2000) notifying that LD slag may be used as a soil conditioner after certain processing such as crushing, washing, and addition of rock phosphates. LD slag contains 29% calcium in the form of CaO. LD slag also contains phosphorous in the form of P_2O_5 . Thus, use of LD slag has a limiting to ground limestone and is used regularly to reduce the need of liming on acidic soil [53]. Steel slag has also been used as amendment for metal-contaminated soils after proper environmental assessment [54, 55, 56].

Use as a fertilizer. Attempts have been made in Tata Steel, India, to use LD slag after grinding to 300 mesh as a soil conditioner in paddy fields, tea gardens, etc. [57]. Nippon Kokan Corporation (NKK) Japan has developed a process to produce eco-friendly slow-release potassium silicate fertilizer from the slag that shows less release effect rather than conventional fertilizers [58]. Many experimental works have been conducted for the production of fertilizers from LD slag, semi-calcined dolomite, and ammonium sulfate, and their agricultural applications for agro-forestry and pasture farming. The potential economic benefits of applying this new fertilizer to the soil were also evaluated [59]. According to soil type and agricultural use, by adding a concentration of LD slags between 1.5 and 5.0 tons/ha it is possible to achieve an increase in soil pH and hence to improve the soil quality and productivity. Experimental works were also carried out using pulverized LD slag for growing vegetables and crops like tomato, potato, onion, spinach, and wheat in acidic soil [60].

Use for road making and floor preparation. With increasing environmental awareness, the waste utilization of steel plants has become an attractive alternative to disposal. For the sustainable development of the steel industry, innovative environmental solutions should be applied. Nippon Slag Association in Japan is using LD slag in port and harbor construction [61]. LD slag boulders are used for floor preparation and in road making for its high hardness and cementing properties. Many steel plants are selling more than 50% of LD slag for construction and ground filling. The LD slag has proved to be an excellent railway ballast material and is being used by Indian Railways. In the Durgapur Steel Plant (Steel Authority of India), the LD slag is sold in the form of boulders for road making. Due to the presence of lime and magnesia, LD slag absorbs moisture and CO_2 from the atmosphere to form hydroxides and carbonates, which leads to volume expansion or swelling in road or building materials. This problem can be overcome by weathering the slag for a duration of 6 to 9 months for the hydration of free lime before its use [62].

Use in cement making for replacement of clinker. In India, cement manufacturers are unwilling to take advantage of the LD slag as a low cost raw material for cement manufacture, whereas its use in cement making is commercialized in China. At Tata Steel, India, a project was initiated in collaboration with Lafarge India for use of LD slag for cement making [57]. In a comparison of LD slag and BF slag, LD slag has higher CaO content and acts as an activator and gives better strength, though the presence of P_2O_5 creates corrosion in reinforced concrete structure. If only 10% LD slag is used in cement, then the P_2O_5 content will be around 0.3%, which is not so harmful in Portland slag cement (PSC), because low P_2O_5 in PSC reacts with alkali contributing additional strength of cement [63]. Thus, it is not possible to use more than 10% LD slag in PSC. Due to the presence of iron oxide in LD slag, it forms a phase, tetracalcium aluminoferrite which has an adverse effect on cement quality. This ferruginous part of LD slag can be separated by magnetic separation [64].

Use in sinter plant after removal of phosphorus. Removal of phosphorus from LD slag is a better option for recyclable iron making processes. Many authors prefer physical processes like magnetic separation, flotation, dual phase

separation, etc. for the same. In magnetic separation study, particles with high magnetic susceptibility are separated by a light magnetic field, and weaker magnetic particles will be separated by a strong magnetic field. Therefore, heterogeneous magnetic fields of different intensities can separate different particles. However, this is not a very effective way of dephosphorization [65–66]. A number of workers have performed chemical treatment (pyrometallurgical) of LD slag [67]. Phosphorus is also removed through evaporation by adding silicon to the Fe–P–C alloy obtained slag with carbon. During reduction of converter slag in an electric furnace, it is possible to form two different phases: one metallic and other nonmetallic [68]. The reduction of phosphorus in molten slag containing 8.3% Al_2O_3 and 3.5% P_2O_5 with basicity of CaO/SiO_2 of 1.1 at 1735 K, 1823 K, and 1893 K has been studied. It shows that temperature has an effect on the reduction of phosphate by graphite. The possibility of reduction of phosphorus by CO gas at 1823 K and the increase in reduction rate with increasing CO gas flow rate has also been investigated. It was concluded that the reaction rate of P_2O_5 was not controlled by diffusion of the P_2 gas phase product but by the chemical reaction [69].

At Tata Steel, a two-stage crushing facility at the raw material bedding yard has been found to be adequate to crush the raw material to the desired size (90% of the material to -3mm) for sinter making [70]. It has been reported that high gradient magnetic separation (HGMS) was able to separate around 50% of P from the LD slag. It was also possible to remove around 70% of phosphorus from slow cooled slag by HGMS. Slow cooling of LD slag promotes mineral grain growth and formation of calcium phosphate as fine grained crystal [71]. Hot metal with a phosphorus content of 0.09–0.16% was treated in a ladle with a dephosphorization agent consisting of LD slag, iron oxide, or lime, and the phosphorus content of hot metal was reduced to 0.020–0.060 or 0.003–0.020%. By refining the dephosphorized hot metal in the LD converter, extra low phosphorus steel having a phosphorus content of less than 0.005% was obtained [72]. A study on bacterial leaching for the removal of P from LD slag was carried out by using specific bacteria for P dissolution, namely *Frateruria aurantia*. The studies were undertaken at 10% (v/v) inoculation. It was possible to remove around 72.17% P from the LD slag [73]. The phosphorus solubilization efficiency was studied at different pulp densities, incubation periods, NaCl concentrations, and at different initial pH of the medium. About 46.87% of P could be solubilised as P_2O_5 from LD slag at 5% pulp density after 24 days of incubation [74].

Use in recovery of different metal values. The metal values recovery from LD slag was carried out by different techniques. Out of these techniques, the smelting reduction technique was carried out for valuable metals recovery, i.e., vanadium and chromium using a Tamman furnace. The recoveries of metal from LD slag are as high as 98% at 1600°C in 30 min [75]. This process was carried out by addition of a small quantity of mineral additive to the molten slag followed by crystallization of the slag. The additive acts as nuclei for crystallization of dicalcium silicate in the slag, and the breaking of slag produces 65–80% slag and 10–15% chips [76]. It was also reported that the most harmful components in LD slag are phosphorus and sulfur, which are to be removed before use either in the sintering plant or the blast furnace. In the Bhilai Steel Plant, India, LD slag was used in the blast furnace but later discontinued due to the high sulfur and phosphorus content [77]. However, the slag is not suitable in cement making due to the presence of a high percentage of iron oxide. The study has been carried out by magnetic separation techniques, and it was found that the combination of low and high intensity magnetic separation of ground LD slag at $63\mu\text{m}$ in the wet process is effective [42].

Use for wastewater treatment. The use of steel slag in industrial wastewater treatment has received intensive attention in recent years. Due to the porous structure and large surface area of steel slag, it is easy to separate from water due to its high density. A high adsorption capacity of steel slag was observed in the treatment of mercury-containing seawater [78]. The steel slag has been used as a low cost adsorbent for arsenic in aqueous systems, showing 95–100% removal efficiency at pH 2. The removal mechanism included the coprecipitation of the analyte from the solvent and its adsorption in CaCO_3 [79]. The removal of copper from wastewater using steel slag was conducted by adsorption and precipitation [80]. Additionally, steel slag can be used as a separate adsorbent to remove aqueous ammonium nitrogen [81], phosphorous [82], and phenol [83].

Use in CO_2 capture and flue gas desulfurization. CO_2 is one of the primary greenhouse gases and a large contributor to climate change. Thus, carbon capture and storage (CCS) research has been the focus of CO_2 reduction technology. With the current CO_2 sequestration routes, mineral CO_2 sequestration is regarded as a potentially important technology due to its benefits such as environmental friendliness and permanent trapping of CO_2 in the form of carbonate and without the need for post-storage surveillance for CO_2 leakage [84]. CO_2 gas is stored by allowing magnesium or calcium oxides in silicate

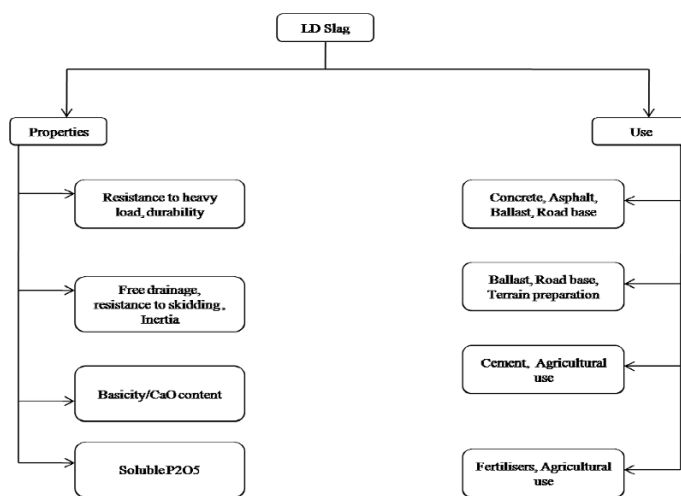


Fig. 4. Schematic representation of LD slag utilization in various fields.

TABLE 5. Important Properties, Uses, Advantages, and Disadvantages of LD Slag

Properties	Uses	Advantages	Disadvantages
Resistance to heavy load, durability	Concrete, asphalt, ballast, road base	Greater hardness, better adhesion, greater stability and reduced wear	Greater weight compared to natural rock
Free drainage, resistance to skidding, inertia, hydraulic property	Ballast, road base, terrain preparation, base course materials	Greater hardness, better adhesion	Impact on logistics and transport costs
Basicity/CaO content	Cement, agricultural use	Replacing the use of clinker, reducing energy consumption and CO ₂ emissions	Emissions of airborne pollution in the form of dust, gases, noise, and vibration when operating machinery
Soluble P ₂ O ₅	Fertilisers/soil conditioner, agricultural use	Amending acid soil and improving plant growth	Possible leaching of heavy metals, potential risk to biosphere

minerals to react with carbon dioxide and form carbonates in mineral carbonation [85]. It is possible to store CO₂ in carbonate form using steel slag slurry under mild conditions of temperature and CO₂ pressure though steel slag contains a large amount of CaO [86]. The method of flue gas desulfurisation includes wet, dry, and semidry processes, among which the wet limestone/lime method is most widely used. It was also concluded that agglomeration gas desulfurization with steel slag was feasible [87]. The experiment was carried out on wet flue gas desulfurization with scrap slag powder residue. It was inferred that a more than 60% wet desulfurization rate could be achieved with a reasonable design and suitable operation by using steel slag. However, this technology is still limited to the laboratory research stage [88]. From this study, it can be confirmed that LD slag may be used in different fields due to its various properties. The uses, advantages, and disadvantages are shown in Table 5 and Fig. 4.

Conclusions. From the above study, it can be concluded that the steel industry is now focused on increasing the recycling of LD slags day by day to conserve energy and natural resources and ultimately improve production. New technologies and/or the improvement of existing technologies have been investigated and developed in order to achieve the ambitious target of “zero-waste” in the incoming years. The effective utilization of LD slags turns into a high-value added product and allows improving the steel plant competitiveness. On other hand, the sustainable use of slags contributes to natural resource saving. Thus, the use of LD slag in different fields produces not only economic but also ecological advantages, since their use

has led to resource conservation and thus solves the disposal problems. This paper demonstrates the significance of LD slag and its utilization.

Due to its high lime content, LD slag can replace lime addition in steelmaking. It can also be used for road making and floor preparation, cement making for replacement of clinker, and recovery of metal values. The phosphorus-enriched slag can also be used as a fertilizer for agricultural purposes and as a soil conditioner for acidity correction of soil. The presence of endemic phosphorus in LD slag is sometimes high, which restricts its reutilization in iron production and steelmaking. The amount of phosphorus can be reduced by physical, chemical, and biological means. As phosphorus is intimately associated with other elements in slag, bioleaching may be an ideal approach for its removal from the LD slag. Also it is possible to use LD slag for recovery of metal values, CO₂ capture and flue gas desulfurization and wastewater treatment through LD slag by applying alternative techniques. However, dephosphorization consumes fluxes and produces a high phosphorus slag, which again needs to be disposed of. Therefore, reuse and recycling of LD slag after removal of phosphorus seems to be a better approach. This will not only solve the present-day problem of LD slag but will also lead to the achievement of zero waste status and sustainable utilization of byproducts of the steel industry.

A detailed study on steel manufacturing with waste management of LD slag reveals that it can be cost effective if handled properly. For reuse of LD slag, after tapping of heat, the slag can be treated under a slow cooling process. The three phases (dicalcium silicate, dicalcium ferrite, and wustite) can be separated. After separation, the iron-rich portion (wustite) can be recycled for iron manufacture or steelmaking, and the lime-rich portion (dicalcium ferrite) can be converted to Mg–Mn-wustite by adding a mixture of metallic powder and coke breeze. If the P content is within tolerable limits in dicalcium ferrite, it can be used directly in iron manufacture or steelmaking. The P-rich portion (dicalcium silicate) can be used for fertilizer making. On the other hand, LD slag can be used for landfilling after checking its long-term leaching properties.

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