

Sustainable Utilization of Spent Pot Lining (SPL) Non-Carbon Portion by Co-Processing in Cement Industries

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Abstract

Spent Pot Lining (SPL) is hazardous waste generated from the degradation of Hall-Héroult cells in the aluminium smelting process, where aluminium is extracted from alumina using electrolysis. The typical life span of a cell is three to six years. The pot de-lining process produces waste containing carbon and refractory materials. Presence of fluoride and cyanide compounds, high alkalinity and heavy metals handling, transportation, storage and disposal of SPL require special care.

The Central Pollution Control Board (CPCB) has established a Standard Operating Procedure (SOP) for utilizing the carbon portion, which is established with authorized carbon recyclers. The density of SPL refractory portion is typically within a range 1.4–2.2 t/m³, the pH ranging from 9.5 to 12.5, fluoride concentration is greater than 50 mg/L as per toxicity leaching characteristic procedure (TCLP) and it has compressive strength that averages 20–30 MPa with a typical maximum value of 50 MPa. Cement plants can use SPL from aluminium smelters as an alternative raw material and fuel due to its high carbon content and high calorific value. Co-processing in cement industries is the most efficient approach for eliminating landfilling and ensuring sustainable waste management. This process leaves no residue, as the incombustible inorganic content of waste materials is incorporated into the clinker matrix. The high temperature varies from about 850 °C to 1800 °C and turbulence in cement kilns provide an exceptional destruction removal efficiency (DRE) of over 99 % for all waste types. Refractory part needs to be crushed to below 20 mm size prior to co-processing in cement kilns, hence crusher units, consisting of jaw crusher and vertical shaft impactor (VSI), were installed at Mahan (Singrauli, India), an unit of Hindalco Industries Ltd., along with pollution control devices to bring down the size of the refractory part in the range of < 20 mm and then dispatch it to cement industries.

Similarly, the segregation of the SPL-refractory portion into an acceptable size was a challenge faced by Hindalco's HiraKud unit in clearing an acquired liability of a legacy stockpile of approximately 80–100 kt. Through multiple design iterations, a double-decker vibrating screen with a capacity of 200 t/day was developed, capable of screening material to an -8 mm fraction. This setup enabled the dispatch of 20 kt of screened SPL fines for co-processing in high-temperature cement kilns, ultimately leading to the clearance of the entire legacy stock.

Keywords: Spent pot lining (SPL), Resource recovery and utilization, Sustainability, Zero waste to landfill.

1. Introduction

Mahan Aluminium, a unit of Hindalco Industries Ltd., is situated in Village Orgari, Bargawan, in the Singrauli district of Madhya Pradesh. The plant has the Pechiney AP36 smelter technology supplied by Rio Tinto Aluminium, and its integrated carbon plant is based on Fives Solios technology. The captive power plant consists of six units of 150 MW each, developed using BHEL technology. Commissioned in 2013, the facility currently operates with an aluminium production capacity of 398 kt/y and has 360 pots in one potline.

The Hirakud Smelter was established in 1959 with an initial capacity of 10 kt/y, it was subsequently expanded to 216 kt/y by 2013. The smelter has two distinct types of pots, namely 85 kA and 235 kA. The 235-kA line consists of 80 GAMI pots, while the 85-kA lines have 564 pots. Between 2006 and 2008, the 85-kA potlines were converted to prebake point-break technology from Søderberg technology. These pots, integral to our production processes, rely on a sophisticated array of materials for their lining, including fire bricks, calcium silicate boards, carbon blocks, dry impervious materials, silicon carbide-nitride blocks, all meticulously chosen to withstand the rigors of continuous operation over extended periods.

The aluminium smelting industry, a key segment in global non-ferrous metal production, uses the Hall-Héroult process for extracting aluminium from alumina. This process, though efficient in terms of metal production, generates a substantial quantity of hazardous waste known as Spent Potlining (SPL). SPL is classified as a scheduled hazardous waste under various national and international environmental regulations due to the presence of toxic substances such as fluoride, cyanide, heavy metals, and high alkalinity components [1]. The material arises from the gradual degradation of carbon cathodes and refractory linings in the cells, which typically require re-lining every three to six years [2].

SPL is conventionally divided into two components: the carbonaceous fraction and the refractory fraction. While the utilization of the carbon portion has been increasingly streamlined through authorized carbon recyclers [3], the handling and productive use of the refractory portion remain a logistical and technical challenge [4]. Notably, the refractory fraction, characterized by a high compressive strength (20–50 MPa), a high alkalinity (pH 9.5–12.5), and elevated fluoride levels (> 50 mg/L based on TCLP tests), poses significant issues in terms of transport, processing, and disposal [5].

To address the environmental and economic concerns associated with SPL disposal, cement industries have emerged as a viable co-processing solution. The high-temperature conditions of cement kilns (ranging from 850 °C to 1800 °C) and their superior Destruction and Removal Efficiency (DRE > 99 %) provide a sustainable path for the total thermal destruction of hazardous constituents without residual waste. Furthermore, the inorganic content of SPL becomes part of the clinker matrix, aligning with circular economy principles [6].

Hindalco Industries Ltd. has pioneered practical applications of SPL co-processing in India, particularly at its Mahan and Hirakud units. At Mahan, an integrated crushing unit (Figures 1 and 2) was developed to reduce refractory sizes to < 20 mm, facilitating their use in cement kilns. In Hirakud, a legacy stockpile of 80–100 kt of SPL refractory waste was effectively processed using a customized double-decker vibrating screen system Figure 3 with a throughput of 200 t/day. This setup enabled the dispatch of 20 kt of screened fines to cement plants, contributing significantly to the clearance of the inherited stockpile [7].



Figure 1. Image of spent pot lining crusher including bagfilters.

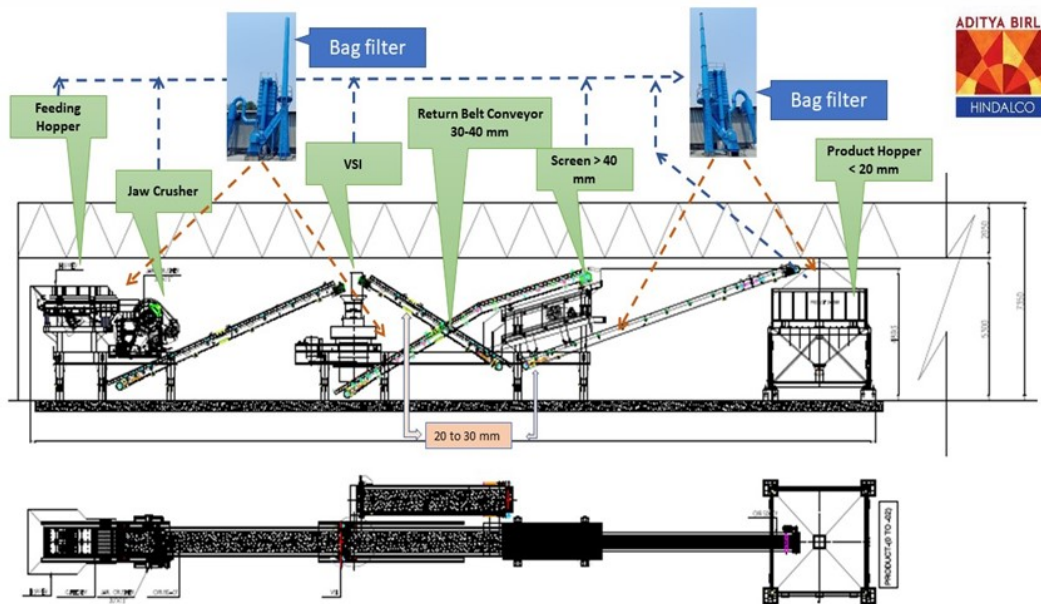


Figure 2. Schematic diagram for SPL crusher.



Figure 3. Left: Screen belt conveyor view, Right: Side view of double-decker vibrating screen capacity 200 t/day.

2. Literature Review

2.1 The Disposal and Management of Spent Pot Lining (SPL)

SPL refractory presented environmental and operational challenges due to its hazardous characteristics. SPL typically contains residual cryolite, fluoride compounds, cyanide, and heavy metals, which categorize it as a toxic waste stream under various national and international regulatory frameworks, including those defined by the Basel Convention and India's Hazardous Waste Management Rules [1, 13].

2.2 Characterization and Hazards of SPL

Numerous studies have examined the physicochemical composition of SPL, particularly focusing on its biphasic nature, where the first cut (carbon portion) and second cut (refractory portion) exhibit distinct chemical and mechanical properties [8]. The carbon-rich first cut often contains volatile organic compounds and unreacted cryolite, whereas the refractory section, composed mainly of brick, insulation, and bath residues, is highly alkaline and laden with fluoride ions [5]. Fluoride leachability exceeding 50 mg/L (TCLP) and high compressive strength values up to 50 MPa make SPL refractory handling and size reduction particularly difficult [9].

2.3 Global SPL Management Approaches

Globally, various treatment options have been proposed, including thermal treatment, chemical stabilization, vitrification, and landfilling. However, landfilling has become increasingly discouraged due to environmental liability, cost, and space constraints [10]. In contrast, the co-processing of SPL in cement kilns has gained significant attention as a sustainable alternative. This method leverages the calorific value of the carbon portion and mineral content of the refractory portion, effectively converting SPL from waste to resource [6].

2.4 Co-processing in Cement Kilns

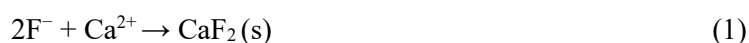
The co-processing of industrial waste such as SPL in cement kilns offers several advantages, including complete thermal destruction, no residual waste, and the reuse of inorganic fractions in clinker formation. Research indicates that the high-temperature zone of cement kilns (up to 1800 °C) provides favorable conditions for the destruction of toxic compounds with a DRE exceeding 99.99 % [11]. Moreover, kiln co-processing reduces reliance on virgin fuels and raw materials, thereby contributing to a circular economy and lowering carbon emissions [12].

2.5 Example Chemical Reactions in Cement Kiln Co-Processing of SPL

In cement kilns, the extreme conditions – high temperatures (~1450 °C) and a strong alkaline environment (pH > 12) – facilitate the incorporation or neutralization of many hazardous constituents from SPL, especially fluoride, heavy metals, and sulfates.

2.5.1 Fluoride Fixation in Clinker Phase

Fluoride ions (F⁻) react with calcium compounds in the kiln to form calcium fluoride (CaF₂), a stable and low-solubility compound (Equation 1),



Calcium fluoride is thermally stable and becomes physically encapsulated in the clinker matrix, reducing its leachability [13].

2.5.2 Heavy Metals

Heavy metals like Nickel (Ni^{2+}), vanadium (V^{5+}), chromium (Cr^{3+}) are chemically bonded into silicate or aluminate phases of clinker (Equation 2).



Where M^{n+} represents a divalent or trivalent metal ion. This reaction leads to isomorphic substitution within cement minerals like “C2S” (belite, $2\text{CaO}, \text{SiO}_4$) and “C3A” ($3\text{CaO}, \text{Al}_2\text{O}_3$), stabilizing the metals [14].

2.5.3 Sulphate Immobilization

Sulphates present in the non-carbon portion of SPL, primarily as SO_4^{2-} or SO_3 , are effectively immobilized during the high-temperature co-processing in cement kilns. Under kiln conditions ($\sim 1450^\circ\text{C}$), these sulphate compounds react with calcium and alumina components to form calcium sulfoaluminate minerals such as ettringite (Equation 3) and monosulfate. These phases are stable in the highly alkaline environment of cement and help trap the sulphate ions within the clinker matrix, significantly reducing their potential for leaching [15].



2.6 SPL Utilization in India

In India, the Central Pollution Control Board (CPCB) has outlined a Standard Operating Procedure (SOP) for the safe handling and utilization of SPL carbon. However, guidelines for the refractory portion are still evolving. Hindalco Industries Ltd. has implemented some of the most significant SPL recovery systems at its Mahan and Hirakud units, addressing legacy SPL stockpiles through mechanical crushing, vibrating screen segregation, and co-processing partnerships with cement plants [7]. As the result of utilizing the crushed refractory portion of SPL, Hindalco Industries Ltd. at Mahan Aluminium achieved a Zero Waste to Landfill certification, with a waste diversion rate of 99.84 %. While several international smelters have achieved near-zero SPL landfill disposal through integrated recovery solutions [16], Indian operations are only recently scaling similar innovations, underlining a need for continued research, optimization, and policy support. The feasibility of co-processing SPL refractory waste in cement kilns has been demonstrated, but these case studies are often isolated, they lack detailed process engineering data, and they are rarely documented in peer-reviewed literature. Furthermore, most studies do not adequately explore on-site segregation, size reduction technologies, or long-term performance metrics related to co-processed SPL in clinker formation. This limits the replicability and scalability of such solutions across diverse industrial settings. Additionally, there is insufficient research on the design optimization of material handling systems, such as crushers and vibrating screens, specifically adapted to the abrasive and chemically active nature of SPL refractory waste.

3. Materials and Methods

3.1 Study Site and Waste Source

The study was conducted at the Mahan Aluminium Unit of Hindalco Industries Ltd. The primary material under investigation was the refractory portion of SPL waste. SPL refractory waste primarily consisted of a mixture of alumina, silica, carbon residues, sodium compounds, and

entrapped fluoride compounds, the chemical characteristics of the SPL refractory portion were conducted at well-established hazardous waste analysis laboratory (Tables 1 and 2).

Table 1. Physical characteristics of SPL refractory portion.

S.N.	Parameters	Test Method	Unit	Min	Max	Standard deviation
1	pH at 250 °C	USEPA SW-846 9045D	---	9.95	12.5	1.093
2	Moisture Content @1050 °C	IS 2720 (Part-2)	%	1.44	1.65	0.087
3	Loss of ignition at 5500 °C (Dry basis)	SEPL/SOP/HW/06	%	13.78	16.54	1.206
4	Calorific Value (Dry basis)	IS:1350(P-02)2010	Cal/g	0	0	0.000
5	Density	ASTM D 5057-2017	g/cm ³	1.41	2.22	0.341
6	Flash Point	USEPA SW-846 1030	°C	0	0	0.000
7	Reactive Cyanide	SEPL/SOP/HW/04	---	Absent		
8	Reactive sulphide	SEPL/SOP/HW/05	---	Absent		
9	Paint Filter Liquid Test	USEPA SW-846 9095B	---	Not Applicable		
10	Liquid Released Test	USEPA SW-846 9096	---	Pass		
11	Water Soluble Halides (as Cl)	USEPA SW-846 5050 9252 9253	%	0.18	0.33	0.065
12	Water Soluble Organics	APHA 2540	%	0.016	0.022	0.011
13	Water Soluble Inorganics	APHA 2540	%	0.36	0.58	0.100

Table 2. Chemical characteristics of SPL refractory portion.

S.N.	Parameters	Test Method	Unit	Min	Max	Avg.	Standard deviation
1	Fluoride (F ⁻)	USEPA 1310 & APHA 23rd EDN 4500 F C	mg/L	50.1	841	226.25	≈ 410
2	Arsenic	USEPA 1311 & 200. 7	mg/L	0.78	6.92	3.85	≈ 3.35
3	Barium	USEPA 1311 & 200. 7	mg/L	0.13	0.42	0.297	≈ 0.192
4	Cadmium (Cd)	USEPA 1311 & 200. 7	mg/L	0	0	< 0.05	≈ 0
5	Chromium	USEPA 1311 & 200. 7	mg/L	0.06	0.85	0.507	≈ 0.382
6	Lead (Pb)	USEPA 1311 & 200. 7	mg/L	0.71	0.71	0.71	≈ 0.355
7	Manganese (Mn)	USEPA 1311 & 200. 7	mg/L	0.05	2.21	0.93	≈ 0.954
8	Mercury (Hg)	USEPA 1311 & 200. 7	mg/L	0	0	< 0.05	≈ 0
9	Selenium (Se)	USEPA 1311 & 200. 7	mg/L	0.11	0.11	0.11	≈ 0.055
10	Silver (Ag)	USEPA 1311 & 200. 7	mg/L	0	0	< 0.05	≈ 0
11	Ammonia (NH ₃)	USEPA 1310 & APHA 23rd EDN 4500 C	mg/L	1.07	1.8	1.43	≈ 0.773
12	Cyanide (CN)	USEPA 1310 & APHA 23rd EDN 4500 CNE/F	mg/L	1.32	1.32	1.32	≈ 0.66
13	Sulphide as H ₂ S	USEPA 1310 & APHA 23rd EDN 4500 SF	mg/L	0	0	< 2.0	≈ 0
14	Nitrate (Nitrate to Nitrogen)	USEPA 1311 & IS 3025 (Part 34:1988)	mg/L	1.95	59.63	18.29	≈ 27.78
15	Antimony (Sb)	USEPA 1310 & 200. 7	mg/L	7.76	7.76	7.76	≈ 3.88
16	Beryllium (Be)	USEPA 1310 & 200. 7	mg/L	0	0	< 0.05	≈ 0
17	Cobalt (Co)	USEPA 1310 & 200. 7	mg/L	0.39	0.39	0.39	≈ 0.195
18	Copper (Cu)	USEPA 1310 & 200. 7	mg/L	0.6	3.76	2.18	≈ 1.802
19	Molybdenum (Mo)	USEPA 1310 & 200. 7	mg/L	2.59	2.59	2.59	≈ 1.295

Table 2. (Cont.) Chemical characteristics of SPL refractory portion.

S.N.	Parameters	Test Method	Unit	Min	Max	Avg.	Standard deviation
20	Nickel (Ni)	USEPA 1310 & 200. 7	mg/L	0.09	17.01	8.55	≈ 8.490
21	Thallium (Th)	USEPA 1310 & 200. 7	mg/L	2.58	2.58	2.58	≈ 1.29
22	Vanadium (V)	USEPA 1310 & 200. 7	mg/L	0.12	17.19	4.628	≈ 8.385
23	Zinc (Zn)	USEPA 1310 & 200. 7	mg/L	0.05	0.39	0.197	≈ 0.173
24	Hexavalent Chromium	USEPA 1310 & APHA 3500 B	mg/L	< 0.05	< 0.05	< 0.05	≈ 0

3.2 Material Characterization

In the present study, Representative SPL refractory samples were collected and characterized for physicochemical properties as per Hazardous and other waste management Rule 2016 [17]. The physicochemical characterization (Table 1) of the non-carbon portion of SPL revealed moderate alkalinity, with a pH range of 9.95 to 12.5 (standard deviation: 1.093), indicating the material's caustic nature. The moisture content was relatively low (1.44–1.65 %), while the loss on ignition ranged from 13.78 % to 16.54 %, reflecting the presence of combustible or volatile matter. Importantly, the calorific value was recorded as below detection limit, confirming the material's non-combustible nature. Other physical properties, such as density, ranged from 1.41 to 2.22 g/cm³. Both flash point and reactive cyanide/sulfide tests returned negative results, indicating low reactivity and absence of volatile or reactive components. Liquid release behavior was confirmed to meet regulatory requirements, with the Paint Filter Liquid Test marked as not applicable and the Liquid Released Test resulting in a pass as sample in solid state. Low levels of water-soluble halides (0.18–0.33 %), organics (0.016–0.022 %), and inorganics (0.36–0.58 %) were observed, suggesting limited mobility of soluble contaminants under normal conditions. These results support the classification of the SPL non-carbon residue as a low-reactivity, non-flammable, and physically stable material suitable for co-processing in cement kilns.

Chemical analysis (Table 2) of leachate derived from the SPL non-carbon fraction i.e. refractory portion revealed wide-ranging contaminant levels. Notably, fluoride exhibited extreme concentrations (50.1–841 mg/L; avg. 226.25 mg/L), far exceeding environmental safety thresholds, and nitrate, nickel, and vanadium also showed elevated and inconsistent levels (nitrate max: 59.63 mg/L; nickel max: 17.01 mg/L), indicating potential environmental hazards if land-disposed. Conversely, toxic elements like cadmium, mercury, and silver were below detection limits, suggesting selective contamination. These findings highlight the importance of adopting co-processing in cement kilns as a sustainable alternative, where high kiln temperatures and alkaline conditions enable complete destruction or incorporation of hazardous constituents into the cement matrix without harmful emissions or leaching potential [18].

The chemical composition of the SPL non-carbon fraction, expressed as oxides, reveals that alumina (Al₂O₃) and silica (SiO₂) are the dominant constituents, ranging from 30–36 % and 34–36 %, respectively. These high levels are typical of refractory materials used in aluminium smelting cells. The loss on ignition (LOI) was recorded between 20–22 %, indicating the presence of volatile or decomposable compounds, such as fluorides or residual carbonates. Other oxides were present in lower proportions, including iron oxide (Fe₂O₃) at 2.3–2.7 %, calcium oxide (CaO) at 3–5 %, magnesium oxide (MgO) at 0.34–0.61 %, and sulfur trioxide (SO₃) at 7.0–8.3 % (Table 3). The elevated SO₃ content could be attributed to sulfate compounds formed during cell operation or SPL storage. This oxide profile demonstrates the mineralogical compatibility of the SPL residue with cement raw meal, supporting its use as an alternative raw material in cement manufacturing through co-processing. Furthermore, compressive strength tests, performed using a universal testing machine (UTM), showed average strength values between 20–30 MPa, with a

maximum observed strength reaching approximately 50 MPa, confirming the mechanical integrity of the cement matrix incorporating SPL residue [19].

Table 3. Composition of SPL mixed dust/fines.

Unit	Loss on ignition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃
%	20–22	34–36	30–36	2.3–2.7	3.0–5.0	0.34–0.61	7.0–8.3

3.3 Size Reduction Arrangement for Pre-processing for SPL Refractory Portion

To make the refractory fraction suitable for co-processing in cement kilns, it had to be reduced to a particle size of < 20 mm. The crushing unit installed at the Mahan site comprised technical details (Table 4) and Analysis details of VSI Rotor material (Table 5) includes the following:

1. A Jaw Crusher (for primary crushing) to reduce large blocks to manageable size.
2. A Vertical Shaft Impactor (VSI) (for secondary crushing) to achieve finer size fractions.
3. Dust suppression systems and Pollution control devices, i.e. bag filters were integrated to ensure safe handling and environmental compliance including mechanical sweeping machines.

Table 4. Technical details of SPL crusher components.

	Primary crusher	Vertical shaft impactor (VSI)	Vibrating screen
Make	SAEC	SAEC	SAEC
Model	PSJ0703	VSI800	VS1405
Capacity	50 t/h	50 t/h	50 t/h
Power requirement	50 HP (37.3 kW)	120 HP (89.5 kW)	10 HP (7.5 kW)

Table: 5-Analysis details of the VSI rotor material.

Elements		C, %	Si, %	Mn, %	S, %	P, %
Specification EN-8	Min	0.35	0.05	0.60	---	---
	Max	0.45	0.35	0.90	0.055	0.055
Test values		0.375	0.256	0.743	0.019	0.022

At the Hirakud unit, legacy SPL refractory stockpiles (~80–100 kt) were processed using a custom-engineered double-decker vibrating screen (Figure 3). Initially, at Hirakud began segregating SPL through manual screening, which was time-consuming and resulted in low production rates of approximately 3–4 t/day. The second version of the screening system, a reciprocating screen developed with in-house resources, was unsuccessful. However, the third version, a rotary screen also developed in-house, proved effective and achieved a production rate of 10–12 t/day of screened material. This equipment was designed through multiple iterations with a throughput capacity of 200 t/day and get 8-mm fines suitable for dispatching to cement industries.

3.4 Packaging and Transportation of Hazardous Waste

The non-carbon fraction of Spent Pot Lining (SPL), classified as hazardous waste due to its high fluoride and alkali content, was packaged and transported in strict accordance with the provisions of the Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016, under the Ministry of Environment, Forest and Climate Change (MoEF & CC) [17]. Special care was taken to ensure safe handling to prevent environmental contamination and protect human health. Prior to transportation, the hazardous waste was appropriately labeled in compliance with Form 8 of the 2016 Rules. A comprehensive Safety Data Sheet (SDS) was prepared and included

with each consignment, detailing the chemical composition, hazards, and safety measures associated with the material [17, 20, 21]. Only transporters authorized by the relevant regulatory authorities were engaged for the movement of the waste. Packaging was undertaken using jumbo bag capacity of one tonne, featuring UN certification and static protection. Each bag was fitted with an inner liner to prevent dust emission. Crushed SPL was filled into these containers within a controlled environment equipped with dust suppression measures. Transportation was carried out using GPS-enabled vehicles that were clearly marked as “Hazardous Waste Transportation Vehicles” (Figure 4). These vehicles were equipped with essential safety equipment, including spill containment kits, fire extinguishers, and emergency communication systems. In compliance with regulatory requirements, prior intimation was given to both the State Pollution Control Boards (SPCBs) of the state of origin and the destination before handing over the waste to the transporter. Transport routes were strategically planned to avoid densely populated and environmentally sensitive areas in order to minimize potential risks. Each consignment was accompanied by a hazardous waste manifest to ensure traceability and full regulatory compliance from the point of generation to the co-processing facility [17].

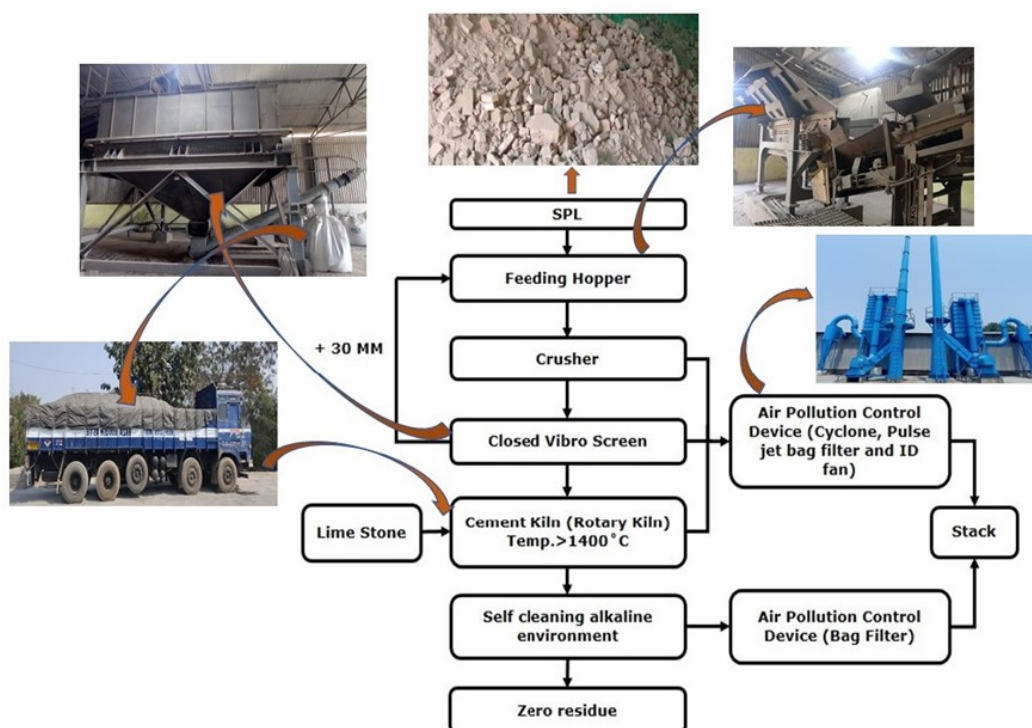


Figure 4. Systematic procedure for handling SPL hazardous material.

3.5 Co-processing in Cement Kilns

The screened and crushed SPL refractory waste was co-processed in cement kilns at partner cement plants. The temperature in the cement kiln process varies from about 850 to 1800 °C. Excess level of Oxygen and counter flow operation with flue gases moving in a direction opposite to the materials lends a high degree of turbulence to the process. The presence of an alkaline reducing environment (lime) and the pre-heating of the raw materials by a pre-heater tower (> 100 m tall) acts as an ideal scrubber for hot flue gases before they are emitted into the atmosphere. The 3-T's, Time, Temperature and Turbulence in cement kilns provides an extremely high destruction removal efficiency (DRE) for all waste types (> 99.999 %) [11]. Co-processing leaves no residue as the incombustible inorganic content of the waste materials was incorporated in the clinker matrix. Key parameters ensured were:

1. Kiln temperature: Maintained between 850–1800 °C

2. Destruction and Removal Efficiency (DRE): > 99 % for organics and hazardous compounds
3. Residue Management: No ash or post-processing residue was generated, as inorganic content was fully incorporated into clinker.

4. Conclusions

The present investigation confirms that the non-carbon refractory fraction of Spent Pot Lining (SPL) can be effectively and safely utilized through co-processing in cement kilns. Based on a comprehensive physicochemical evaluation aligned with the Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016 [17], the SPL samples were found to be non-flammable, with low moisture content, no detectable reactive sulphides or cyanides, and limited liquid release potential—classifying them as low-risk solid industrial waste. Despite the presence of elevated concentrations of certain leachable contaminants—particularly fluoride (up to 841 mg/L), nitrate (up to 59.63 mg/l), nickel (up to 17.01 mg/L), and vanadium (up to 17.19 mg/L)—these can be effectively immobilized under the extreme thermal and alkaline conditions of cement kiln operations, significantly minimizing their environmental release. The chemical oxide composition of the refractory material, rich in alumina (30–36 %) and silica (34–36 %), with supplementary levels of CaO, MgO, Fe₂O₃, and SO₃, indicates strong mineralogical compatibility with the raw meal used in cement production [19]. In addition, mechanical performance tests of the resulting cementitious matrix demonstrated compressive strength values between 20–30 MPa, with a peak around 50 MPa, further validating the structural integrity of the blended product [19].

The screened material of the non-carbon fraction of Spent Pot Lining (SPL) was co-processed in the clinkerization process at selected cement plants. At one plant, SPL was fed into the kiln at a rate of 50 metric tonnes per day, representing approximately 0.5 % of the total raw material feed of 10 000 t/day. Similarly, another cement plant utilized 50 t/day of SPL, accounting for around 0.42 % of its total daily feed capacity of 12 000 t. These controlled addition rates were implemented to evaluate the compatibility of SPL with the cement production process. The results indicated that co-processing SPL at these proportions is technically feasible and does not negatively impact clinker quality, process efficiency, or environmental emissions [22, 17].

The material processed through the SPL crusher was supplied to cement plants in quantities amounting to less than 25 % of their approved annual limit of 20 000 metric tonnes for SPL hazardous waste. This level of utilization demonstrated no adverse impact on clinker quality or environmental emissions, clearly indicating the safe and effective co-processing of the non-carbon fraction of SPL in cement kilns, as verified through trials conducted at the cement plants based on their approved annual capacity [17, 23].

Overall, these findings strongly support the sustainable utilization of SPL non-carbon refractory waste in cement manufacturing, offering a technically viable and environmentally responsible alternative to landfilling or other disposal methods. Such integration aligns with international best practices in industrial ecology and circular economy, contributing to resource conservation, waste minimization, and carbon footprint reduction in both the aluminium and cement sectors [16, 19].

The sustainable management of hazardous industrial waste remains a pressing environmental challenge, particularly for aluminium smelters generating SPL. The non-carbon portion of SPL, often high in inorganic salts and heavy metals, poses significant leaching risks if not properly handled. The adoption of the SPL crusher and double decker screen, strengthened our waste management by enabling the recovery of valuable materials from hazardous waste. This has led to a significant reduction in disposal costs and the complete elimination of landfill use, earning us the Zero Waste to Landfill certification. In conclusion, co-processing of SPL's non-carbon

residue in cement industries presents an environmentally sound and industrially viable pathway for mitigating SPL-associated risks, provided strict emission and quality monitoring is maintained throughout the process.

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