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Valorization and Safe Management of Spent Pot Lining (SPL): A Critical Review of Applications, Environmental Challenges, and Disposal Strategies

Antonio Clareti Pereira*
Ph.D. in Chemical Engineering Federal University of Minas Gerais (UFMG) – Department of Chemical Engineering Belo Horizonte – MG – Brazil
E-mail: claretipereira@gmail.com

Abstract

Spent Pot Lining (SPL), a hazardous waste generated during the Hall-Héroult process, amounts to 1.4–1.8 million tonnes annually, with China accounting for nearly 60% of global production. Rich in fluorides, cyanides, and reactive metals, SPL poses serious environmental risks, including soil and groundwater contamination and toxic gas emissions. Traditional disposal methods such as landfilling and encapsulation are increasingly unsustainable, prompting the development of advanced thermal, hydrometallurgical, and integrated treatment technologies. These approaches enable the recovery of valuable products, such as fluoride salts, alumina, and carbon, while reducing hazardous residues. Additionally, cement co-processing has emerged as a practical large-scale solution, achieving both neutralization of toxic compounds and energy recovery. Industrial case studies from China, Norway, and Brazil demonstrate >95% landfill diversion, proving the technical feasibility of circular SPL management. However, challenges remain, including high CAPEX, regulatory inconsistencies, and SPL heterogeneity. Future progress depends on the harmonization of international policies, the advancement of clean technologies, and the creation of sustainable supply chains to achieve zero-waste, carbon-neutral aluminium production.

Keywords: Spent Pot Lining (SPL). Thermal treatment.. Hydrometallurgical process. Cement co-processing. Circular economy. Hazardous waste management. Fluoride recovery. Aluminium smelting. Environmental regulations. Sustainable recycling

1. Introduction

Despite increasing SPL generation, there is no consolidated framework addressing both regulatory gaps and valorization pathways, especially in emerging economies.

The global production of primary aluminium has continued to increase in recent years, driven by demand from sectors such as transportation, packaging, construction, and electrical applications. Primary aluminium production remains energy-intensive and contributes significantly to greenhouse gas emissions, although recent reports indicate pressure to reduce its environmental footprint and emissions intensity[1,2].

The aluminium smelting process, usually by the Hall-Héroult method, involves electrolytic reduction of alumina in carbon-lined pots. At the end of the pot life, the cell lining (typically composed of an insulating refractory lining plus an interior carbon lining) degrades due to thermal, chemical and mechanical stresses and must be replaced. This worn-out lining is known as spent pot lining (SPL), a hazardous waste due to its content of fluorides, cyanides, and other reactive metal components[2,3].

These residues present major environmental and regulatory challenges. When stored or disposed improperly, SPL can leach toxic ions (e.g., fluoride, cyanide), produce toxic or explosive gases in contact with water (such as hydrogen cyanide, ammonia), and contaminate soil, water, and air[2]. Regulatory frameworks in many jurisdictions classify SPL as hazardous waste, which imposes strict requirements for its handling, transport, treatment and disposal. International guidance such as the "Sustainable Spent Pot Lining Management Guidance" by the International Aluminium Institute emphasizes compliance with environmental regulation, risk assessment, and stakeholder engagement[3].

Given these issues, there has been increasing interest in valorization of SPL components (fluorides, alumina, carbon, refractory materials), as well as in improved treatment or neutralization technologies. Recent studies propose methods combining thermal and chemical-leaching treatments, low-pressure heat treatments, and novel material recovery routes[4,5]. Moreover, the aluminium industry is under growing societal, regulatory, and market pressure to reduce its hazardous waste generation as part of broader sustainability and circular economy goals[2,5].

Justification for this review: although several studies and guidance documents have addressed SPL generation, hazard characterization, treatment and reuse, there appears to be no comprehensive synthesis focused on literature from 2020-2025 that integrates recent technological advances, regulatory trends, environmental assessments, and case studies. Such a review is needed for both scientific and industrial stakeholders to assess promising routes, understand emerging risks, and inform policy.

Objectives of this review are:

This review synthesizes recent advances in SPL treatment, compares global regulatory approaches, and identifies research gaps for sustainable management

Methodology:

A systematic literature search was conducted in Web of Science, Scopus, and Google Scholar for peer-reviewed articles published between January 2020 and the present. Search terms included "spent pot lining", "SPL treatment", "aluminium primary waste", "fluoride removal SPL", "hazardous waste SPL", etc. Studies were included if they addressed SPL

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generation, characterization, treatment or valorization. Guidance documents and regulatory reports were also considered. Screening followed PRISMA principles: duplicates removed; titles/abstracts screened for relevance; full texts assessed for inclusion based on criteria above.

2. Spent Pot Lining (SPL): Generation and Characteristics

2.1. Formation of SPL in the Hall-Héroult Process

In the Hall-Héroult process, alumina (Al_2O_3) is dissolved in a molten cryolite bath (primarily Na_3AlF_6) with additions of other fluxes, at temperatures around 950-970 °C, between a carbon (graphite) cathode and carbon anodes. Over time, the lining of the electrolytic pot (composed of side walls, bottom cathode blocks, ramming paste, insulation and refractory materials) undergo thermal, chemical, and mechanical degradation due to high temperatures, electrolysis reactions, infiltration of molten electrolyte, attack by fluorides, sodium, and deposition of metallic species. At end of life, the pot is decommissioned, and the lining is removed, generating the waste known as Spent Pot Lining (SPL)[3,6].

SPL is typically divided into two fractions, commonly called "first cut" and "second cut". The first cut (or 1st cut) corresponds to the carbon-rich portion: the worn cathode carbon/graphite blocks, sidewall carbon, and residual carbon matrix infiltrated by electrolyte. The first cut is usually higher in carbon content, relatively more homogeneous in terms of carbon phase, but still contains contaminants (fluorides, residual cryolite, metallic sodium or other species, cyanides)[6,7]. The second cut corresponds to the refractory components: bottom block refractory flush, insulating bricks, ramming paste and other ceramic/refractory materials; lower in carbon, higher in alumina, silica, and other refractory oxides; more variable in composition and less homogeneous[7].

Quantitative composition data for first cut SPL (from recent studies) report carbon contents on the order of 55-65 wt % in the first cut, with significant amounts of sodium fluoride (NaF), cryolite, alumina, calcium fluoride (CaF_2) etc. For example, in a Chinese study Wang et al. (2020) found ~65 % carbon, ~15 % NaF in first cut SPL; calorific value ~22.6 MJ/kg[7]. Another more recent study by Sommerseth et al. (2025) describes that after low-pressure high-temperature treatment, first cut SPL can reach carbon purity up to ≈98 wt % after removal of electrolyte remains[3].

These structural and chemical features (carbon matrix + contaminant infiltrations) reflect both the design of the cells (prebaked or Søderberg), the lifetime of the pot, the degree of cleaning prior to de-lining, and the material of cathode & refractory bricks[3,6].

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Figure 1 shows. schematic representation of the formation of Spent Pot Lining (SPL) in a Hall-Héroult electrolytic cell, highlighting the "first cut" (carbon cathode layer) and the "second cut" (refractory and insulating materials).

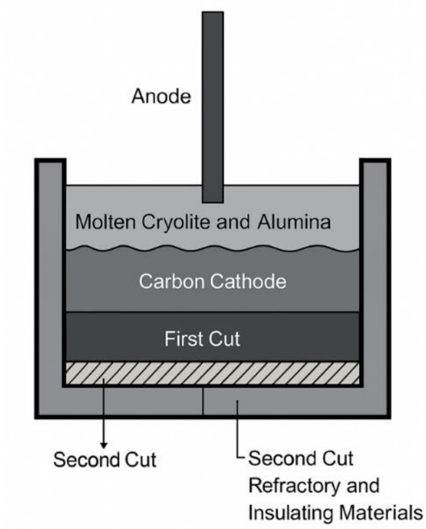

Figure 1. Cross-section of a Hall-Héroult cell showing SPL formation with distinct first and second cut layers.

This diagram illustrates the structural composition of an electrolytic cell and the progressive degradation of its layers. The clear distinction between first and second cut SPL is essential for understanding differences in chemical composition and treatment approaches. While the first cut is carbon-rich and has potential for energy recovery, it also contains hazardous contaminants such as fluoride and cyanide, requiring careful pre-treatment. The second cut, composed of refractory and insulating materials, poses challenges for recycling due to its heterogeneity and lower added value. Proper identification of these layers supports the selection of efficient, safe, and sustainable valorization strategies.

2.2. Formation of SPL in the Hall-Héroult Process

The Hall-Héroult process is the dominant technology for primary aluminium production worldwide. It consists of the electrolytic reduction of alumina (Al_2O_3) dissolved in molten cryolite (Na_3AlF_6), typically operating at temperatures between 950 and 970 °C. The electrolytic cell, or pot, is composed of a carbon cathode lining at the bottom and carbon anodes at the top. During operation, alumina is continuously fed into the bath, where it dissociates, and aluminium ions are reduced at the cathode to form molten aluminium, while carbon anodes are consumed, releasing CO_2 gas[3,6].

The cathode lining is a complex multilayer structure designed to withstand high temperatures, chemical attack, and mechanical stress. It usually includes:

- Carbon blocks forming the cathode where aluminium metal is deposited.
- Ramming paste, which fills gaps between the blocks, providing structural stability and electrical continuity.
- Refractory bricks and insulating materials, which protect the external steel shell from heat loss and maintain structural integrity[6,7].

Over time, the harsh operational environment leads to degradation of the lining through several mechanisms: infiltration of molten cryolite and metallic sodium into the carbon, chemical reactions producing sodium cyanide (NaCN) and other compounds, mechanical erosion from bath movement, and thermal cycling stresses. As degradation progresses, the pot efficiency decreases and, eventually, the entire lining must be replaced[3,7].

When a pot reaches the end of its operational life, the removed material is termed Spent Pot Lining (SPL). SPL is traditionally classified into two distinct fractions:

- First Cut SPL: This upper layer consists primarily of carbon materials (cathode blocks and sidewall carbon) heavily impregnated with electrolyte and metallic contaminants. It typically contains 55–65 % carbon, significant levels of sodium fluoride, cryolite, aluminium oxides, and hazardous compounds such as cyanides. This layer has higher calorific value and is the primary focus for energy recovery or chemical treatment[6].
- Second Cut SPL: The lower layer includes refractory bricks, insulation materials, and ramming paste residues. It has low carbon content and is richer in alumina, silica, and other refractory oxides. Due to its heterogeneity and low energy potential, it is more challenging to recycle and often requires separate handling and disposal[6,9].

The differentiation between first and second cut SPL is essential for selecting appropriate treatment technologies. First cut SPL is more reactive and hazardous due to its fluoride and cyanide content, whereas second cut SPL poses lower immediate chemical risk but represents a larger bulk volume of inert material[3,7].

Table 1. Typical chemical composition ranges for First Cut and Second Cut Spent Pot Lining (SPL). The First Cut, mainly composed of carbonaceous materials, shows high levels of carbon and fluoride salts, along with hazardous compounds such as cyanides, making it highly reactive and challenging to handle. In contrast, the Second Cut contains predominantly refractory and insulating materials, with higher concentrations of alumina and silica, lower

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reactivity, and limited potential for energy recovery. These differences are critical for selecting appropriate treatment, recycling, and disposal strategies.

Table 1. Typical composition of First Cut and Second Cut SPL

Component	First Cut SPL (carbon lining)	Second Cut SPL (refractory lining)
Carbon (C, wt-%)	40 – 75	0 – 20
Alumina (Al_2O_3, wt-%)	0 – 10	10 – 50
Sodium (Na and Na compounds, wt-%)	8 – 17	6 – 14
Fluoride (F and fluoride salts, wt-%)	10 – 20	4 – 10
Silica (SiO_2, wt-%)	0 – 6	10 – 50
Calcium oxide (CaO and Ca compounds, wt-%)	1 – 6	1 – 8
Cyanide (total, wt-% or ppm)	0.01 – 0.50 (100–5000 ppm)	0 – 0.10

Notes and interpretation

- The values represent **typical ranges**; actual compositions vary significantly depending on smelter technology (prebake vs. Søderberg), pot lining age, raw material quality, and delining practices[6,8,10].
- The **weight ratio of First Cut to Second Cut** in total SPL mass is commonly around **55 % : 45 %**, but this can differ by plant[6].
- First Cut SPL has higher reactivity and hazard potential due to its **carbon content**, **fluoride salts**, and **cyanide**, making it the main target for energy recovery and chemical neutralization.
- Second Cut SPL consists mostly of refractory and insulating materials, making it less reactive but **bulkier and harder to recycle**, often requiring separate handling or disposal[7,9].

Figure 2. Bar chart comparing the average composition of First Cut and Second Cut SPL, highlighting the higher carbon and fluoride content in the First Cut and the predominance of alumina and silica in the Second Cut.

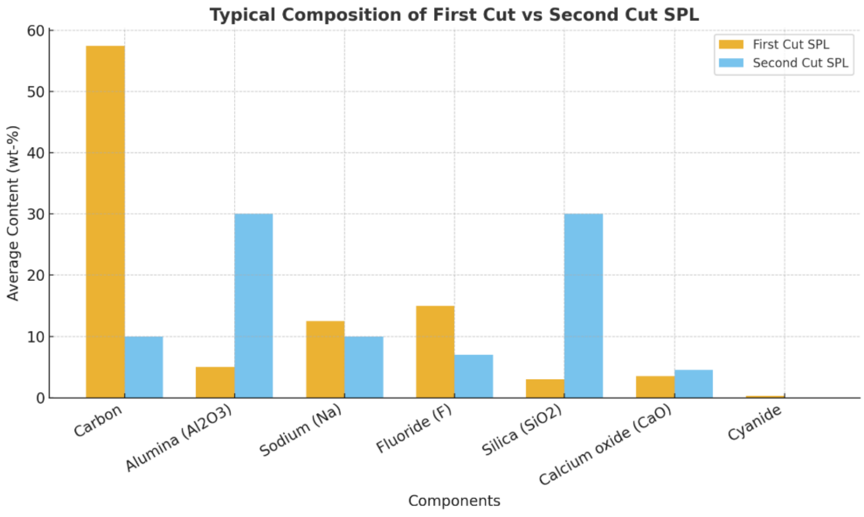

Figure 2. Comparison of the average composition of First Cut and Second Cut SPL.

2.3. Chemical and Physical Characterization

The chemical composition of Spent Pot Lining (SPL) is highly variable and depends on factors such as cell technology (prebake or Søderberg), raw material quality, operational conditions, and the degree of cleaning during delining. In general, SPL contains **carbon**, **fluoride salts**, and **aluminium compounds**, along with various minor hazardous species. The main chemical constituents of SPL include **carbon (C)** from the cathode blocks, **sodium fluoride (NaF)**, **aluminium fluoride (AlF_3)**, and **cryolite (Na_3AlF_6)** derived from the molten bath infiltration [1,10]. Trace amounts of **cyanides (NaCN)** are formed through reactions between sodium, nitrogen, and carbon at high temperatures, while **heavy metals** such as arsenic (As), vanadium (V), and chromium (Cr) may be present in minor concentrations, particularly in smelters processing bauxite with elevated impurity levels[4,10].

From a **physical standpoint**, SPL exhibits heterogeneous properties. *First Cut* SPL tends to have a lower bulk density (typically **1.1–1.5 g/cm³**) due to its high carbon content and porosity, while *Second Cut* SPL, rich in refractory oxides, has a bulk density ranging between **1.8 and 2.4 g/cm³** [6]. Particle size distribution after mechanical delining and crushing typically ranges from coarse fragments (>50 mm) down to fine powders (<0.5 mm). Studies have reported **average particle sizes** of 2–10 mm after primary crushing, with fines increasing reactivity and dust generation during handling[6,7]. Porosity levels are also significant, with total porosity often exceeding 25–35%, influencing both the leaching behavior of soluble salts and the kinetics of thermal treatment [7].

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The **hazardous nature of SPL** stems from its reactivity and toxicity. When SPL meets water or moisture, several hazardous reactions can occur:

- **Hydrogen gas (H_2)** evolution due to reaction of metallic sodium residues with water, creating an explosion risk.
- **Ammonia (NH_3)** and **hydrogen cyanide (HCN)** generation from the hydrolysis of cyanide salts.
- **Highly alkaline leachates**, rich in fluoride and sodium ions, which are toxic to aquatic life and can corrode infrastructure [1,10].

The high concentration of soluble fluorides (e.g., NaF and cryolite) poses significant environmental concerns due to the potential contamination of groundwater and soil. Toxicological assessments indicate that even small amounts of fluoride leachate can exceed environmental quality standards, necessitating careful containment and treatment during storage and processing of SPL[4,11].

Because of these combined chemical and physical hazards, SPL is classified as a **hazardous waste** under many international regulations, such as the European Waste Catalogue and the U.S. Resource Conservation and Recovery Act (RCRA). Effective characterization of SPL—covering both its chemical profile and physical properties—is essential for selecting appropriate handling, treatment, and valorization routes, as well as for ensuring regulatory compliance and environmental protection[10,11].

Table 2 summarizes the typical physical properties of Spent Pot Lining fractions. *First Cut SPL* shows a **lower bulk density** and **higher porosity**, reflecting its carbon-rich, porous structure, while *Second Cut SPL* has **greater density** and **lower porosity**, consistent with its refractory composition. The wide particle size distribution after crushing indicates strong heterogeneity, which affects handling, reactivity, and the design of treatment processes

Table 2. Typical physical properties of First Cut and Second Cut SPL

Property	First Cut SPL (Carbon-rich layer)	Second Cut SPL (Refractory-rich layer)	References
Bulk density (g/cm^3)	1.10 – 1.50	1.80 – 2.40	6,7
True density (g/cm^3)	2.05 – 2.25	2.45 – 2.85	6
Total porosity (% vol)	30 – 40	20 – 30	6,7
Moisture content (% wt)	< 0.5 (typical after storage under dry conditions)	< 0.5	10

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Property	First Cut SPL (Carbon-rich layer)	Second Cut SPL (Refractory-rich layer)	References
Typical particle size after crushing (mm)	0.5 – 50 (wide range due to heterogeneity)	0.5 – 50	6,7
Dominant particle size fraction (mm)	2 – 10	2 – 20	7
Angle of repose (°)	35 – 40	38 – 42	6

Critical Notes

- The **high porosity** of First Cut SPL facilitates rapid penetration of water or leachates, increasing risks of hazardous reactions, such as hydrogen or cyanide gas release [1,11].
- Particle size distribution plays a key role in dust formation and the kinetics of thermal or chemical treatment; finer fractions require special dust control systems [7].
- Low moisture levels are essential during storage to prevent violent reactions and uncontrolled leachate generation[10].

2.4. Global volumes and regional outlook

How much SPL is generated?

Industry datasets indicate an average of approximately 25 kg of SPL per tonne of primary aluminium produced. Based on this factor, recent global estimates place annual SPL generation between 1.4 and 1.8 million tonnes. The International Aluminium Institute (IAI) reported around 1.6 Mt in 1312, a figure confirmed by more recent reviews, while a 1325 technical assessment cited ~1.42 Mt/y based on current production and recovery assumptions[1,2].

Where is SPL generated? – Following primary aluminium production.

Because SPL generation is directly proportional to smelter output, the geographic distribution of primary aluminium production drives SPL generation patterns:

- China is the dominant producer, responsible for nearly 60% of global aluminium production, with ~43 Mt of primary aluminium in 1324, generating the highest SPL volume worldwide[12].
- Other major producers include India, Russia, United Arab Emirates (UAE), Canada, Australia, Bahrain, Norway, and Brazil. In 1324, Canada produced ~3.3 Mt and Brazil ~1.1 Mt of primary aluminium, resulting in significant SPL generation in these regions[13,14].

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- Aggregated data from IAI confirm sustained high output levels through 1324–1325, reinforcing SPL generation pressures globally and the need for adequate treatment infrastructure[2,12].

First cut vs second cut contribution:

For planning and management purposes, the total SPL mass can be divided into approximately 55% first cut (carbonaceous material) and 45% second cut (refractory material), though this ratio varies with pot design and operational practices[6].

Implications:

Regions experiencing rapid capacity growth—particularly China, parts of Asia, and the Gulf Cooperation Council (GCC) countries—face the greatest challenges in SPL management. This highlights the need for regional treatment facilities, standardized characterization protocols, and the development of markets for treated SPL (e.g., cement production, mineralization, fluoride recovery) to ensure environmentally safe and economically viable solutions[1,2,6].

Uncertainty notes:

The 25 kg/t specific generation factor represents an industry-wide average. Older cell designs tend to produce more SPL per tonne of aluminium, while modern high-amperage, energy-efficient cells can reduce this figure. Estimations based on country-level production multiplied by this factor provide useful first-order approximations for waste planning but should be refined with plant-specific data[1,6].

Figure 3. Estimated SPL generation by country in 1324, assuming an average of 25 kg of SPL per tonne of primary aluminium produced.

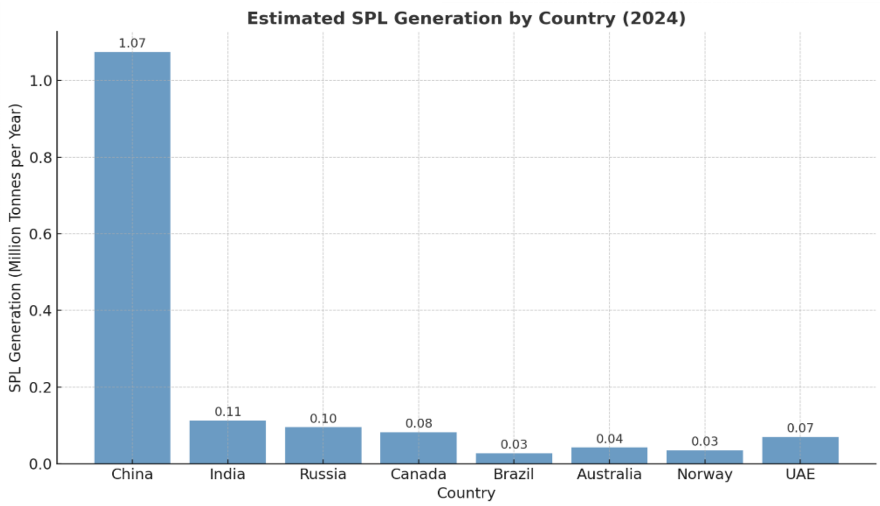

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Figure 3. Estimated SPL Generation by Country (1324).

The graph highlights China's overwhelming dominance, generating nearly 1.1 Mt of SPL annually, which represents close to 60% of the global total. India and Russia follow at a much smaller scale, while countries like Canada, UAE, and Brazil contribute moderate volumes. This geographic concentration implies that Asia and the Gulf region are at the epicenter of SPL management challenges, requiring large-scale treatment infrastructure and strict environmental controls. In contrast, lower-volume producers, although facing smaller absolute quantities, may encounter economic barriers to centralized treatment, making regional cooperation and innovative recycling markets essential for sustainable SPL handling.

3. Environmental and Regulatory Aspects

3.1. Classification as Hazardous Waste

Spent Pot Lining (SPL) is universally recognized as a hazardous industrial waste due to its chemical reactivity and toxic components. Its classification is defined by several international and national regulatory frameworks that establish criteria for hazardous waste identification, handling, and disposal.

United States (EPA – Resource Conservation and Recovery Act, RCRA):

The U.S. Environmental Protection Agency (EPA) classifies SPL under hazardous waste codes K088 for "spent potliners from primary aluminum reduction" due to the presence of cyanide compounds and reactive fluoride salts[15]. This classification subjects SPL to strict regulations regarding storage, transportation, treatment, and reporting, including compliance with Subtitle C of RCRA.

European Union (EU – Waste Framework Directive):

In the EU, SPL falls under the European Waste Catalogue (EWC) code 3,4,10* for "spent potlining from aluminium smelting" with an asterisk indicating hazardous waste status [16]. This designation is linked to the risk of leaching fluoride, alkali compounds, and other toxic species that pose threats to both human health and the environment. The EU’s Waste Framework Directive (Directive 2008/98/EC) mandates traceability, permitting, and safe disposal routes for this category of waste.

Brazil (ABNT NBR 10004):

According to Brazilian standard ABNT NBR 10004:2004, SPL is classified as Class I – Hazardous Waste, as it exhibits characteristics of toxicity and reactivity. This classification

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is based on the leachate test results, where soluble fluoride and cyanide concentrations exceed the thresholds established by the standard[17]. Consequently, Brazilian environmental agencies (e.g., IBAMA and state agencies) require SPL to be managed under strict control with mandatory environmental licensing for storage and treatment facilities.

Hazardous reactions and toxic gas generation:

A critical safety concern is the release of toxic gases when SPL comes into contact with water or humid environments.

- Hydrogen cyanide (HCN): Generated by the hydrolysis of sodium cyanide (NaCN) and related cyanide species present in the first cut SPL. Even small amounts can create lethal concentrations in confined spaces[1,14].

- Ammonia (NH_3): Produced through reactions between nitrogen compounds and alkali metals in the SPL matrix. Although less toxic than HCN, NH_3 poses serious respiratory hazards and contributes to atmospheric pollution[1].
- Hydrogen gas (H_2): Released from reactions of residual metallic sodium or aluminium with water, creating a flammable and potentially explosive atmosphere [1,25].

These hazardous gas-generating reactions are why SPL must be stored in dry, controlled environments and transported in sealed containers to prevent moisture ingress. Many smelters implement inert gas blanketing or ventilation systems in storage areas to mitigate explosion and poisoning risks.

Global implications:

The consistent classification of SPL as hazardous waste across major jurisdictions reflects the shared understanding of its environmental and health risks. However, there remain differences in threshold limits and compliance requirements, which can complicate international cooperation on SPL treatment technologies and recycling markets. Harmonizing these criteria is essential for developing sustainable, cross-border solutions for SPL management[16,17].

Table 3 compares how SPL is classified as hazardous waste across major jurisdictions. While the **underlying hazards are universally recognized**—fluorides, cyanides, and reactivity—the **thresholds and codes differ**, creating challenges for international transport and treatment of SPL. For example, the U.S. EPA uses a **specific code (K088)**, while the EU applies

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a **catalogue-based system** with a hazard flag (*), and Brazil uses a **class-based approach** under **ABNT NBR 10004**.

Table 3, International criteria for SPL hazardous waste classification

Region / Standard	Waste Code	Key Hazardous Criteria	Examples of Thresholds / Conditions
United States (EPA – RCRA)	K088 – Spent potliners from primary aluminium reduction	Presence of cyanides and reactive fluoride salts; potential for toxic gas generation	*Cyanide (total)* > 590 mg/kg; Reactive wastes that generate toxic gases (e.g., HCN, NH_3) upon contact with water
European Union (EU – Waste Framework Directive, EWC)	10 03 04* – Spent potlining from aluminium smelting	Toxicity, leachability of fluoride and alkali compounds	*Fluoride leachate* > 150 mg/L (example national adaptation); Asterisk (*) indicates mandatory hazardous waste handling
Brazil (ABNT NBR 10004:2004)	Class I – Hazardous Waste	Toxicity and reactivity based on leachate tests and hazardous reactions	*Soluble fluoride* > 150 mg/L; *Total cyanide* > 0.2 mg/L; Evidence of hazardous gas generation (HCN, NH_3, H_2)
Canada (CEPA – Canadian Environmental Protection Act)	Aligns with US EPA K088	Cyanides, fluorides, explosive gas potential	Similar to EPA criteria, with federal-provincial regulatory variations
Australia (National Environmental Protection Measures – NEPM)	Managed as hazardous industrial waste	Risk-based assessment of fluoride leachate, cyanide content, gas release potential	Typically requires special permits for storage and transport

a. The **U.S. and Canada** provide explicit codes and quantitative thresholds for cyanides and reactive substances, ensuring clear compliance guidelines.
b. The **EU framework** focuses on harmonization among member states, but national variations in leachability limits can lead to inconsistencies in cross-border SPL management.
c. **Brazil** uses a **toxicological and leachability-based system**, which aligns closely with EU practices but adds specific attention to **gas generation risks**, reflecting operational realities in tropical climates with high humidity.

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d. These differences highlight the **need for global harmonization** of SPL classification to streamline international recycling and disposal efforts while maintaining environmental protection and worker safety.

3.2. International Regulations

The management of Spent Pot Lining (SPL) is governed by a combination of global conventions and local legislation, reflecting its hazardous classification and the need to prevent environmental contamination and cross-border transfer of hazardous waste without appropriate safeguards.

Basel Convention

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (1989) provides the primary international framework for SPL management.

- Under this convention, SPL is explicitly recognized as a hazardous waste due to its content of cyanides, fluorides, and reactive metals, falling under categories A1080 and A2060 for toxic, leachable wastes.
- The convention prohibits international shipment of SPL without prior informed consent (PIC) between exporting and importing countries.
- It requires documentation, safe transport practices, and verification of environmentally sound management (ESM) facilities at the receiving end[18].
- Recent updates emphasize circular economy strategies, encouraging treatment and valorization of SPL within national borders rather than relying on export to other countries for disposal[19].

United States

In the United States, SPL is regulated under the Resource Conservation and Recovery Act (RCRA) as hazardous waste with the specific code K088[20].

- Generators must comply with Subtitle C regulations, including manifest tracking, storage in lined and covered facilities, and reporting requirements.
- SPL disposal in regular landfills is prohibited; only permitted hazardous waste treatment facilities can handle this material.
- The U.S. also enforces strict air quality and occupational health rules to mitigate risks of HCN and NH_3 gas emissions during storage and processing[21].

European Union

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The European Union (EU) manages SPL under the Waste Framework Directive (Directive 2008/98/EC) and the European Waste Catalogue (EWC).

- SPL is listed under EWC code 10 03 04*, where the asterisk (*) denotes mandatory hazardous waste handling[22].
- EU member states must ensure traceability, transport permits, and monitoring of leachate emissions from storage sites.
- The Industrial Emissions Directive (IED) also applies to smelters and SPL treatment plants, setting emission limits for gaseous pollutants, including HF and NOx[22,23].

Brazil

In Brazil, SPL is classified as Class I – Hazardous Waste according to ABNT NBR 10004:2004, with management governed by CONAMA Resolution No. 313/2002 and state-level environmental agency rules [24].

- Storage must occur in impermeable, covered areas with leachate collection systems.
- Treatment and recycling operations require environmental licensing, including risk management plans and emissions monitoring.
- Export of SPL is strictly controlled under Brazil's Basel Convention commitments, requiring government authorization for cross-border movement[25].

Australia

Australia applies a risk-based approach to SPL management under the National Environmental Protection Measures (NEPM).

- SPL is treated as hazardous industrial waste, requiring specialized permits for storage, handling, and interstate transportation[26].
- State governments enforce specific guidelines, with Queensland and Western Australia implementing rules for safe containment and reporting of fluoride and cyanide leachates[35].
- The country has adopted Basel Convention principles into domestic law, aiming to minimize exports and promote local treatment or reuse of SPL.

Critical Analysis

The comparison of regulatory frameworks reveals that, while there is global agreement on SPL's hazardous nature, implementation varies significantly:

- The U.S. EPA has a highly prescriptive system with detailed waste codes and reporting mechanisms.

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- The EU emphasizes harmonization among member states, yet national variations in enforcement persist.
- Brazil and Australia focus on licensing and containment, reflecting the challenges of managing hazardous waste in emerging and resource-intensive economies.
- The Basel Convention plays a crucial role in preventing the uncontrolled movement of SPL between countries, but enforcement gaps remain in regions with limited regulatory capacity.

These differences highlight the importance of international cooperation and standardization, especially as smelters seek to adopt circular economy solutions that involve cross-border recycling markets for treated SPL.

Table 4 highlights the similarities and differences in SPL regulation across global and regional frameworks. While all jurisdictions **classify SPL as hazardous**, their approaches differ:

- The U.S. and EU have specific waste codes and highly prescriptive systems.
- Brazil uses a class-based toxicological system, focusing on licensing and containment.
- Australia applies a risk-based model, granting more flexibility at the state level.
- The Basel Convention acts as a global umbrella, ensuring control over international waste transfers.

Table 4. Comparison of international regulations for SPL management

Region	Legal Framework / Code	Hazard Classification	Key Requirements	Export / Import Rules
Global (Basel Convention)	Basel Convention (1989)	Hazardous waste (Categories A1080 & A2060)	Prior Informed Consent (PIC), documentation, environmentally sound management (ESM)	Strictly controlled, export only with consent and proof of ESM
United States	RCRA Subtitle C – Code K088	Hazardous waste	Manifest tracking, lined storage, permits for treatment facilities, reporting to EPA	Export requires EPA approval and Basel compliance
European Union	Waste Framework Directive 2008/98/EC, EWC 10 03 04*	Hazardous waste (*)	Traceability, transport permits, Industrial Emissions Directive limits for SPL plants	Export only within Basel rules; intra-EU transfer requires notification

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Region	Legal Framework / Code	Hazard Classification	Key Requirements	Export / Import Rules
Brazil	ABNT NBR 10004:2004, CONAMA Res. 313/2002	Class I – Hazardous Waste	Environmental license for storage and treatment, impermeable storage areas, leachate control	Export allowed only with federal authorization and Basel compliance
Australia	National Environmental Protection Measures (NEPM)	Hazardous industrial waste	State permits, monitoring of fluoride/cyanide leachates, risk-based management	Basel compliance integrated into national law

Critical Notes

- The asterisk (*) in the EU's EWC code indicates mandatory hazardous handling, similar to the K088 designation in the U.S.
- Brazil's emphasis on impermeable storage and leachate collection reflects its climatic conditions, which increase the risk of uncontrolled reactions and groundwater contamination.
- Countries aligned with the Basel Convention are moving towards local treatment and valorization, reducing reliance on hazardous waste exports.

These environmental risks have prompted the development of stricter regulations and innovative treatment technologies, discussed in the following sections.

3.3. Environmental Impacts

Improper handling, storage, or disposal of Spent Pot Lining (SPL) poses significant environmental hazards due to its chemical reactivity, high solubility of certain components, and potential for hazardous gas emissions. These impacts primarily affect soil and groundwater through leachate migration and air quality through uncontrolled emissions during storage or treatment.

Soil and groundwater contamination

SPL contains high concentrations of soluble fluorides (e.g., NaF, Na_3AlF_6), cyanides, alkali metals, and trace heavy metals such as arsenic, vanadium, and chromium. When SPL is exposed to rainwater or moisture in uncontrolled storage areas, these components dissolve and leach into surrounding soils, creating alkaline, highly toxic leachates[1,9].

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Studies have reported fluoride concentrations in leachate exceeding 1,000 mg/L, far above drinking water quality limits, posing severe risks to groundwater supplies and aquatic ecosystems[9,27].

- Fluoride ions (F^-) can bind to calcium in soils and water, leading to long-term contamination and bioaccumulation in plants and animals.
- Cyanide species, although present in lower concentrations, are highly toxic and can generate hydrogen cyanide (HCN) gas or persist in water as free or complexed cyanide, posing acute toxicity risks to aquatic life[9].
- Heavy metals such as arsenic and chromium may accumulate in sediments, leading to chronic ecological impacts and potential entry into the food chain 04.

In Brazil and other tropical regions with high rainfall, improperly managed SPL storage sites have been linked to fluoride plumes in groundwater, requiring costly remediation and monitoring efforts[28].

Atmospheric emissions

During storage or disposal of SPL without proper containment, atmospheric emissions can occur due to chemical reactions with moisture and environmental exposure:

- Hydrogen cyanide (HCN) and ammonia (NH_3) are released when cyanides and nitrogen-containing compounds react with water, creating immediate health hazards to workers and nearby populations[9].
- Hydrogen gas (H_2) generation from residual metallic sodium reacting with water creates a flammable and explosive risk, particularly in enclosed storage facilities[1].
- During open-air incineration or uncontrolled thermal treatment, fluoride compounds such as HF and NaF can volatilize, contributing to air pollution and acidification of surrounding ecosystems[27].

Monitoring data from smelter storage areas show that airborne fluoride concentrations can exceed occupational exposure limits when SPL is handled without engineering controls such as covered storage and scrubbers[9].

Critical implications

The dual pathways of leachate migration and airborne emissions underline the importance of integrated SPL management. Effective mitigation strategies include:

- Impermeable storage pads with leachate collection systems.
- Enclosed, ventilated storage facilities with gas capture and treatment.

- Regular groundwater monitoring around storage and disposal sites.
- Adoption of valorization technologies that stabilize hazardous components before disposal[1,28].

Without these measures, SPL poses long-term environmental liabilities and significant regulatory non-compliance risks.

4. Traditional Disposal Practices

Historically, the predominant management route for Spent Pot Lining (SPL) has been land disposal, either through engineered hazardous waste landfills or long-term containment strategies. While these practices remain in use in some regions, they are increasingly viewed as unsustainable due to cost, environmental risk, and regulatory pressure.

4.1. Hazardous waste landfills with impermeable barriers

Engineered hazardous waste landfills are designed with multi-layer impermeable liners, leachate collection systems, and monitoring wells to prevent contamination of soil and groundwater. SPL is placed in sealed cells, often mixed with inert materials to reduce reactivity and dust generation[1,2].

- These facilities are typically lined with high-density polyethylene (HDPE) or clay barriers to contain soluble fluorides and cyanides.
- Gas collection systems may be required to safely vent hydrogen cyanide (HCN), ammonia (NH_3), and hydrogen (H_2) produced by SPL's reactive components.
- Storage sites must comply with stringent environmental monitoring and reporting protocols set by local authorities[16].

While effective at short-term containment, landfills do not neutralize the hazardous compounds in SPL. Over time, liner degradation or operational failures can lead to leachate migration, posing long-term environmental liabilities[2,4].

4.2. Encapsulation and confinement

Encapsulation involves encasing SPL in concrete or polymer matrices, creating monolithic blocks that limit the material's exposure to water and air. This method is often used where landfill space is limited or when smelters aim to stabilize SPL on-site before final disposal[1,3].

- The process typically includes pre-treatment steps such as crushing, drying, and partial neutralization of cyanides and fluorides to reduce reactivity before encapsulation.

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- Encapsulated SPL can be stored in dedicated vaults or industrial landfills as long-term containment structures.

While encapsulation improves physical stability and reduces immediate leachate generation, it remains a temporary solution. Future excavation or structural failure could re-expose hazardous materials, creating environmental risks for future generations[3,16].

4.3. Limitations of traditional disposal

Although landfill and encapsulation techniques have been widely implemented, they face several critical disadvantages:

1. **High costs:**
   a. Construction and operation of engineered hazardous waste landfills involve significant capital and operational expenditure.
   b. Long-term environmental monitoring and maintenance add to the financial burden on smelters and municipalities[2,4].
2. **Long-term liability:**
   a. SPL has remained chemically hazardous for decades, meaning that even well-managed sites can become future environmental liabilities if containment barriers fail[1].
3. **Space constraints:**
   a. As global aluminium production grows, the volume of SPL generated each year (~1.4–1.8 Mt) creates landfill capacity pressures, particularly in regions with limited land availability such as Europe and Asia[4,16].
4. **Regulatory pressure:**
   a. Many jurisdictions, including the European Union and North America, are shifting policies to discourage landfilling of SPL and incentivize recycling and valorization pathways[3].

4.4. Transition towards sustainable alternatives

Due to these limitations, there is a global trend toward replacing traditional disposal with valorization technologies, such as co-processing in cement kilns, chemical recovery of fluorides and alumina, and thermal treatment for material recycling. These approaches aim to reduce the long-term environmental footprint of SPL while generating economic value from its components[1,3].

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Figure 4. Transition from traditional SPL disposal methods, such as landfilling and encapsulation, to sustainable alternatives. Disadvantages of conventional methods include high cost, long-term liability, and limited landfill space.

Figure 4. Traditional Disposal Practices

5. Treatment and Valorization Technologies

The growing environmental and regulatory pressures to eliminate landfilling of Spent Pot Lining (SPL) have accelerated the development of treatment and valorization technologies. These technologies aim not only to neutralize hazardous components such as fluorides and cyanides but also to recover valuable materials like fluoride salts, alumina, and carbon. They can be broadly categorized into thermal, hydrometallurgical, mechanical, and integrated processes.

5.1. Thermal Processes

Thermal methods rely on high-temperature treatment to destroy reactive compounds, recover fluoride salts, or immobilize hazardous species.

5.1.1. Controlled incineration

a. SPL is heated in rotary kilns or fluidized beds under controlled oxygen levels.
b. Cyanides and organic contaminants are thermally decomposed, while fluorides remain in the solid residue for later recovery.
c. Off-gases containing HF and HCN require advanced scrubbing systems to prevent air pollution[1,2].

d. Drawback: high energy consumption and potential emission of hazardous gases if poorly managed.

5.1.2. Vitrification

a. SPL is melted with glass-forming additives (e.g., silica, lime) to produce a glassy, inert material.
b. This process immobilizes fluorides and heavy metals, reducing leaching potential.
c. The vitrified product can be used as a construction aggregate or safely landfilled 29.
d. Limitations: very high operational temperatures (>1,300 °C) and high CAPEX.

5.1.3. Pyrometallurgical recovery

a. At 1,000–1,200 °C, SPL is mixed with reducing agents to recover cryolite, sodium fluoride, and aluminium from the first cut fraction.
b. Pyrometallurgical reactors can produce reusable fluoride salts for smelters, closing the material loop[30].
c. Examples: low-pressure thermal treatment that separates carbon-rich solids from volatilized salts[3].

5.2. Hydrometallurgical Processes

Hydrometallurgical techniques use aqueous solutions to selectively dissolve and recover valuable components.

5.2.1. Acidic leaching

a. Acids such as HCl, H_2SO_4, or HNO_3 dissolve fluoride salts and alumina.
b. Cyanides are typically destroyed via oxidative pre-treatment before leaching to prevent toxic byproducts[31].
c. Requires precise pH control and corrosion-resistant equipment.

5.2.2. Alkaline and saline leaching

a. Alkaline media (e.g., NaOH) can selectively dissolve alumina, leaving carbon and refractory phases intact.
b. Saline leaching uses chloride or sulfate salts at elevated temperatures to mobilize specific fluoride species[7].

5.2.3. Selective recovery

a. Post-leaching, precipitation or crystallization techniques recover purified NaF, AlF_3, and other reusable products.

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b. Effluent treatment is critical to meet discharge standards[27].

Advantages of hydrometallurgy:

a. Lower energy consumption than thermal methods.

b. Greater selectivity and potential for high-purity product streams.

c. Disadvantages include handling large volumes of wastewater and slower processing rates.

5.3. Mechanical Processes

Mechanical treatment provides pre-processing steps that improve the efficiency of thermal or chemical methods.

a. Crushing and milling: Reduce SPL particle size, increasing surface area for leaching or combustion[6].

b. Screening and classification: Separate first cut (carbon-rich) from second cut (refractory-rich) material for targeted treatment[4].

c. Magnetic separation: Removes metallic iron contaminants introduced during pot operation.

Mechanical processes are not sufficient alone to neutralize SPL but are essential for optimizing integrated treatment plants.

5.4. Integrated Process Routes

Modern SPL management increasingly combines thermal, hydrometallurgical, and mechanical operations to maximize resource recovery and minimize waste.

a. Example: mechanical separation followed by thermal volatilization of fluorides and acidic leaching of residual solids for alumina recovery[3,27].

b. Some commercial systems operate as closed-loop processes, recycling recovered fluoride salts directly to the aluminium smelter, creating a circular economy model.

Integrated routes also enable energy recovery from the carbon fraction, e.g., by feeding it into cement kilns or metallurgical furnaces[6].

5.5. Technology Comparison

A comparative evaluation of different SPL treatment technologies is summarized in **Table 5**.

Table 5. Comparative analysis of SPL treatment technologies

Technology	Recovery Efficiency	CAPEX / OPEX	Environmental Impact	Key Outputs
Controlled incineration	Low – destroys hazards but limited recovery	Medium	Moderate, requires advanced gas scrubbing	Neutralized residue
Vitrification	Moderate – stable inert product	High	Low leaching risk, high energy use	Glass-like inert material
Pyrometallurgical recovery	High – fluoride and aluminium recovery	High	Moderate, depends on emission control	NaF, AlF_3, recovered carbon
Hydrometallurgical leaching	High – selective recovery of salts	Medium	Wastewater treatment required	NaF, AlF_3, alumina
Mechanical pre-treatment	Not applicable alone	Low	Minimal, primarily dust control needed	Size-graded SPL fractions
Integrated routes	Very high – circular economy potential	High initial, lower over time	Optimized emissions and resource use	Recovered salts, carbon, alumina

Although hydrometallurgical routes achieve higher selectivity, their operational complexity and wastewater generation pose challenges compared to thermal processes.

Critical Analysis

a. Thermal processes are essential for complete neutralization of cyanides but can be energy-intensive and costly.
b. Hydrometallurgical methods offer high selectivity and recovery of valuable products but require sophisticated effluent management.
c. Mechanical processing is a necessary pre-treatment step, improving downstream process efficiency.
d. Integrated solutions align best with circular economy principles, combining strengths of each method and reducing final waste volume.

Global trends indicate a shift away from simple disposal toward closed-loop recycling, driven by regulatory pressure and economic incentives for resource recovery.

Figure 5. Integrated SPL treatment flowchart showing mechanical pre-processing, thermal and hydrometallurgical processes, and recovery of fluoride salts and aluminium.

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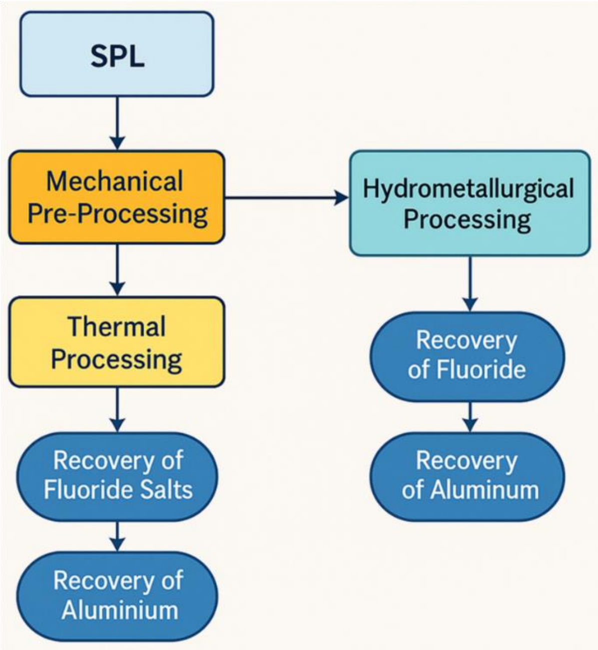

Figure 5. Integrated SPL treatment flowchart

6. Industrial Applications for Treated SPL

The transition from landfilling to circular economy models for SPL management has driven the development of industrial applications for treated SPL. These applications aim to recover economic value while reducing the environmental footprint of the aluminium industry. The main outlets include the cement industry, fertilizers, refractories, ceramics, and emerging niche applications.

6.1. Cement Industry

The cement industry is currently the largest industrial outlet for treated SPL, especially the first cut fraction, which contains high levels of carbon and fluorides. SPL can play two roles in cement kilns:

a. Alternative raw material: providing alumina, silica, and fluorides as mineralizers to improve clinker formation.
b. Alternative fuel: utilizing the calorific value of the carbon fraction to replace fossil fuels[1,2].

Key advantages:

a. Reduction of natural raw material and fossil fuel consumption.
b. High-temperature kilns (>1,450 °C) ensure complete destruction of cyanides and organic contaminants, minimizing environmental risks.

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c. The alkaline environment of clinker formation immobilizes hazardous compounds like fluoride and heavy metals, reducing leachability of the final cement product[32].

Regulatory framework:

a. In Europe, EN 197-1 and related standards govern the composition of Portland cement, requiring testing for leachability and environmental safety before SPL-derived materials are incorporated[32].
b. Brazil follows ABNT NBR 16697:2018, which establishes similar quality control requirements.

Challenges:

a. Variability in SPL composition demands rigorous pre-treatment and quality control.
b. Public perception and regulatory barriers may limit acceptance, especially in markets with strict building codes[2].

6.2. Fertilizer Production

Treated SPL can serve as a source of soluble salts, particularly sodium fluoride (NaF) and sodium aluminate, for fertilizer production.

a. Fluoride salts recovered via hydrometallurgical processes can be converted into micronutrient fertilizers, used in small quantities for specific crops like tea and grapes[30].
b. Sodium salts may be repurposed for industrial fertilizers such as sodium nitrate or sodium phosphate blends.

Considerations:

a. Strict purification steps are necessary to eliminate toxic impurities such as cyanides and heavy metals before agricultural use.
b. Compliance with fertilizer quality standards such as FAO/WHO Codex Alimentarius is mandatory[30].

6.3. Refractories and Ceramic Materials

The second cut SPL, rich in alumina, silica, and residual carbon, can be processed into refractory bricks or ceramic materials:

a. After mechanical separation and stabilization, the alumina content can partially replace bauxite or other alumina sources in refractory production[4].
b. The carbon fraction may be incorporated into specialized refractory products for steelmaking or non-ferrous metallurgy[6].

Benefits:

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a. Reduces reliance on mined raw materials.
b. Adds value to materials that are otherwise difficult to recycle.

6.4. Emerging Applications

New research has explored innovative uses for treated SPL, particularly in environmental engineering and construction sectors.

a. Adsorbents for wastewater treatment:
b. Stabilized SPL has been used to create porous materials with high surface area, effective in adsorbing heavy metals, fluorides, and phosphates from industrial effluents[27].
c. Construction materials:
d. SPL-based composites, including bricks and tiles, have been developed as low-cost building materials, especially for non-structural applications.
e. Pilot studies indicate that encapsulated SPL can meet safety standards when mixed with cement or geopolymer matrices[3].

These emerging applications require further scale-up and long-term testing to validate performance and environmental safety.

Table 6. Summary of SPL Industrial Applications

Application Sector	Recovered SPL Component	Key Benefits	Challenges / Limitations
Cement industry	Carbon, fluorides, alumina	Reduces fossil fuel use, complete destruction of cyanides	Variability in SPL composition, regulatory acceptance
Fertilizer production	Sodium fluoride, sodium salts	High-value fertilizer micronutrients	Requires high purification, strict quality control
Refractories & ceramics	Alumina, carbon	Substitutes natural raw materials	Needs stabilization and blending
Adsorbents for effluent treatment	Porous stabilized SPL	Removes heavy metals and fluoride from wastewater	Limited scale, further testing needed
Building materials	Encapsulated SPL composites	Circular economy and waste valorization	Public acceptance, long-term durability

Critical Analysis

a. Cement kilns remain the most mature and scalable application, aligning with waste co-processing trends worldwide.
b. Fertilizer and refractory applications offer high economic potential but require strict quality controls to prevent agricultural or industrial contamination.

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c. Emerging applications like adsorbents and building materials are promising but currently limited to research and pilot projects.

d. Diversification of SPL outlets is essential to reduce dependence on landfills and move toward a zero-waste aluminium industry.

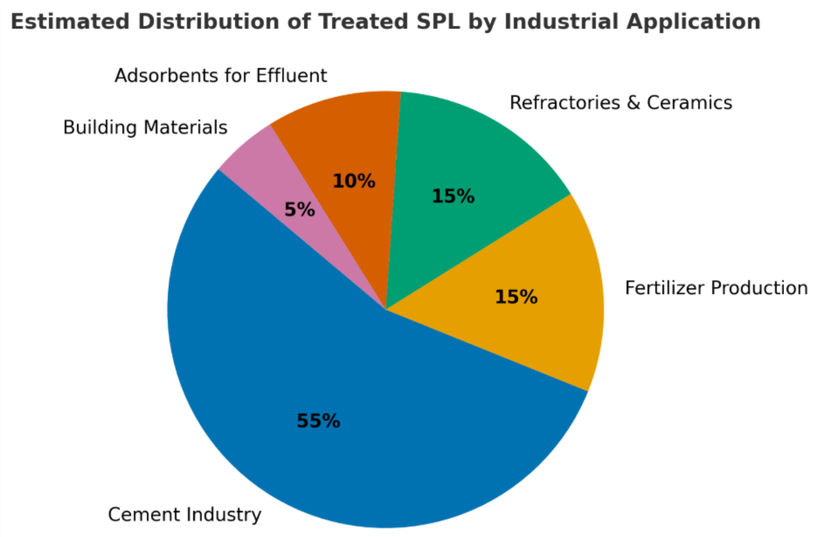

Figure 6. Estimated Distribution of Treated SPL by Industrial Application. Source: Adapted from IAI (2024) and Chen et al. (2022)

7. Case Studies

The global transition from landfilling to valorization and recycling of SPL is supported by several industrial-scale projects. These case studies demonstrate the technical feasibility, environmental benefits, and economic viability of different treatment routes.

7.1. China – Large-scale integrated treatment plants

China, which produces ~60% of the world's primary aluminium, generates over 1.0 Mt/year of SPL. Historically, most SPL was stockpiled or landfilled, leading to severe environmental challenges[2].

a. Integrated SPL treatment plants have been established in provinces such as Henan, Shandong, and Xinjiang, combining mechanical separation, thermal volatilization, and hydrometallurgical recovery[4].

b. Recovered products include fluoride salts (NaF, AlF_3), recycled carbon, and stabilized inert residue for construction use.

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c. In 2023, a plant in Henan achieved a recovery rate of 90% for fluoride salts and processed >120,000 tonnes/year of SPL, representing a circular economy benchmark for the aluminium industry[4].

Environmental and economic impact:

a. Reduction of landfill volumes by >95%, minimizing groundwater contamination.
b. Recovered fluoride salts reduced smelters' operational costs by substituting virgin raw materials.
c. Compliance with China's stricter environmental standards for hazardous waste disposal implemented in 2024[33].

7.2. Norway – Hydro's closed-loop recycling

Norway-based Hydro Aluminium operates a low-pressure, high-temperature SPL treatment plant developed in partnership with research institutions[3].

a. The process thermally separates the carbon-rich fraction from volatilized fluoride compounds under controlled pressure and oxygen levels.
b. Fluoride gases are condensed and purified to produce industrial-grade NaF and AlF_3, which are directly reused in Hydro's primary smelters.
c. The remaining carbon and inert material are repurposed for energy recovery and construction applications.

Key outcomes:

a. Circular process with zero hazardous waste output.
b. Reduction of raw material procurement costs for fluoride salts by up to 40%.
c. Demonstrated scalability with >30,000 tonnes/year SPL capacity[3].

7.3. Brazil – Cement co-processing partnership

In Brazil, the aluminium industry faces challenges with SPL storage due to high rainfall and groundwater sensitivity.

a. A partnership between smelters and cement producers has enabled the co-processing of SPL in Portland cement kilns, following ABNT and environmental regulations[28].
b. Pre-treated SPL is used as both alternative fuel (carbon content) and raw material (fluorides, alumina) for clinker formation.

Results:

a. Destruction of >99% of cyanides and complete neutralization of reactive compounds.

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b. Cement producers reduced fossil fuel consumption by 8–12%, improving economic and environmental performance.

c. Pilot-scale testing has now been scaled up to full industrial operation, processing >15,000 tonnes/year of SPL[1].

7.4. Comparative analysis of treatment routes

A comparative study of plants in China, Norway, and Brazil highlights the diversity of SPL treatment strategies (

Table 7).

Table 7. Comparative summary of large-scale SPL treatment plants

Country	Main Technology	Capacity (t/year)	Year of Implementation	Key Products Recovered	Environmental Impact
China	Integrated (Mechanical + Thermal + Hydrometallurgical)	120,000	2023	NaF, AlF_3, Carbon, Inert residue	Landfill diversion >95%
Norway	Low-pressure thermal separation	30,000	2024	NaF, AlF_3, Carbon	Closed-loop recycling
Brazil	Cement kiln co-processing	15,000	2022	Clinker, Energy recovery	Complete cyanide destruction

7.5. Lessons learned

a. China demonstrates the benefits of scaling treatment infrastructure in regions with massive SPL generation, proving that high recovery rates are feasible when supported by strict regulations.

b. Norway highlights the importance of technological innovation and closed-loop systems to reduce dependence on virgin materials.

c. Brazil showcases how existing industrial assets, such as cement kilns, can be leveraged to create cost-effective and environmentally safe disposal routes.

These cases collectively show that regional context including SPL volume, regulatory environment, and industrial ecosystem, determines the optimal technology mix for sustainable SPL management.

8. Challenges and Research Gaps

Despite recent progress in SPL treatment and valorization, significant barriers remain to achieving full-scale sustainable management. These challenges involve technical, economic, and regulatory factors, as well as gaps in fundamental research.

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8.1. Technical and economic barriers to scale-up

a. High capital costs (CAPEX):
b. Advanced thermal and hydrometallurgical technologies require substantial initial investments, particularly for emission control systems, effluent treatment units, and specialized reactors[1].
c. Many small and mid-sized smelters lack the financial capacity to deploy these systems independently.
d. Operational complexity:
e. SPL is highly heterogeneous, with variable composition between first cut and second cut fractions. This variability demands flexible, modular processing systems, increasing operational complexity and maintenance costs[3].
f. Logistics and infrastructure:
Transportation of SPL is costly due to its hazardous nature, requiring sealed containers and specialized permits. Remote smelter locations further increase supply chain challenges, especially in developing regions[4].

8.2. Lack of standardized regulations

While most jurisdictions classify SPL as hazardous waste, regulatory frameworks differ substantially, creating barriers to cross-border cooperation and trade of recycled SPL products.

a. For example, the EPA's K088 code (USA) has strict thresholds for cyanides and fluorides, while the EU Waste Framework Directive focuses on leachability testing, and Brazil uses ABNT Class I criteria[15].
b. This lack of harmonization complicates technology transfer and international recycling markets, slowing the global adoption of circular economy practices[16].

8.3. Emerging technologies with high potential

Current treatment technologies are dominated by thermal and chemical routes. However, emerging innovative approaches show promise for addressing current limitations:

a. Biotechnological processes:
b. Use of specialized microorganisms to biodegrade cyanides and stabilize fluoride species. Pilot studies indicate potential for low-cost, low-energy pre-treatment steps[27].
c. Electrochemical processes:

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d. Electrochemical oxidation and reduction can selectively destroy hazardous compounds like cyanides or recover valuable ions such as fluoride and aluminium from SPL leachates[31].
e. Digitalization and AI-driven process control:
f. Advanced sensors and machine learning can optimize SPL treatment plant operations, reducing energy consumption and improving product recovery[34].

However, these technologies remain at laboratory or pilot scale, requiring additional research and demonstration projects before industrial implementation.

Critical insight

Bridging these gaps requires multidisciplinary collaboration among researchers, smelters, regulators, and policymakers to create scalable, economically viable, and environmentally responsible SPL management systems.

China's rapid scale-up reflects both regulatory enforcement and the availability of domestic markets for recycled fluoride salts, while Brazil's cement co-processing leverages existing industrial infrastructure

9. Future Perspectives

The long-term vision for SPL management aligns with circular economy principles and global sustainability targets, including carbon neutrality and ESG goals.

9.1. Circular economy and zero waste

Future SPL systems aim to achieve zero-waste aluminium production, where all SPL fractions are valorized:

a. Fluoride salts and alumina are recovered and returned to smelters as feedstock.
b. Carbon fraction is used for energy recovery or as a raw material in refractory and metallurgical industries.
c. Inert residues are stabilized and used in construction materials, such as cement or geopolymers[30].

This closed-loop approach reduces the need for raw virgin materials and minimizes environmental impact, creating a self-sustaining industrial ecosystem.

9.2. ESG integration and carbon-neutral goals

As aluminium producers adopt ESG (Environmental, Social, and Governance) frameworks, SPL management plays a key role:

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a. Reducing hazardous waste footprint supports environmental metrics.
b. Safe working conditions and community engagement improve social responsibility indicators.
c. Transparent reporting and traceability enhanced governance performance[35].

Moreover, co-processing SPL in cement kilns and energy recovery from the carbon fraction can significantly lower carbon emissions, supporting net-zero targets set by global climate initiatives.

9.3. Sustainable supply chain development

To ensure a scalable global solution, future SPL management must integrate sustainable supply chains:

a. Regional treatment hubs serve multiple smelters.
b. Standardized logistics for safe transport and tracking of SPL.
c. Certification schemes for recycled SPL products to ensure market acceptance and consumer confidence[36].

9.4. Research and innovation priorities

The next decade will focus on:

a. Scaling emerging biotechnological and electrochemical processes.
b. Improving data-driven process optimization through AI and real-time monitoring.
c. Establishing global regulatory harmonization to enable efficient recycling markets.

Critical vision

The transformation of SPL management from a waste problem to a resource opportunity will require coordinated action across the aluminium value chain, driving progress toward circular, zero-waste, and carbon-neutral production systems.

Figure 7. Comparative matrix highlighting current challenges in SPL management and future perspectives focused on circular economy, ESG integration, and sustainable supply chains.

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Figure 7. Comparative matrix highlighting current challenges in SPL management and future perspectives

10. Conclusions

This review highlights the critical environmental and industrial challenges associated with Spent Pot Lining (SPL), a hazardous by-product of the primary aluminium production process. SPL management has historically relied on landfilling and encapsulation, which, while effective in the short term, present long-term environmental liabilities, high costs, and limited scalability.

The aluminium industry must prioritize innovation in clean technologies, such as biotechnological and electrochemical routes, while fostering international collaboration to achieve sustainable SPL management.

Industrial case studies from China, Norway, and Brazil prove the technical and economic feasibility of large-scale SPL recycling, showing reductions of over 95% in landfill demand and significant decreases in environmental emissions. However, barriers remain, including high capital costs, regulatory fragmentation, and the need for standardized global frameworks to support cross-border recycling markets.

Future developments should focus on:

a. Emerging technologies such as biotechnological and electrochemical processes, which offer low-energy, selective treatment pathways.
b. Integration of digitalization and AI-driven control systems to optimize SPL treatment plants.

c. Establishing global regulatory harmonization to accelerate sustainable markets for SPL-derived products.

In conclusion, SPL management represents both a challenge and an opportunity. By transforming SPL from a hazardous waste into a valuable resource, the aluminium industry can move closer to zero-waste production, support ESG and carbon-neutral goals, and create a sustainable supply chain. Achieving this vision will require collaboration between smelters, regulators, researchers, and policymakers, fostering innovation and investment in clean, scalable, and economically viable technologies.

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