Life Cycle Assessment of Icelandic Volcanic Pozzolans as Low-Carbon Supplementary Cementitious Materials

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Abstract. The cement industry is a major contributor to global greenhouse gas emissions, predominantly due to clinker production. Supplementary Cementitious Materials (SCMs) represent an effective mitigation strategy, yet conventional SCMs such as Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) are becoming increasingly scarce. Volcanic pozzolans offer a promising natural alternative, and Iceland possesses extensive deposits that have not yet been evaluated from an environmental perspective. This study presents the first cradle-to-gate Life Cycle Assessment (LCA) of Icelandic Volcanic Pozzolan (VPI) production, drawing on primary data from three extraction sites and a planned processing facility in Þorlákshöfn—Lambafell, Litla Sandfell, and Landeyjahöfn—and secondary data from GaBi and Ecoinvent. A declared unit of one tonne of VPI is assessed across all ReCiPe 2016 midpoint impact categories. Results show that VPI's climate change impact of 25.5 kg CO_2-eq/t falls between FA (3–10 kg CO_2-eq/t) and GGBFS (50–80 kg CO_2-eq/t), confirming its competitiveness with established SCMs while offering the strategic advantage of abundant local supply. Marine dredging operations emerge as the dominant environmental hotspot, accounting for approximately 48.1% of total CO_2-equivalent emissions. The findings confirm VPI as a robustly low-carbon SCM and support its large-scale adoption in sustainable cement production.

Keywords: Life Cycle Assessment · Supplementary Cementitious Materials · Icelandic Volcanic Pozzolan · Low-Carbon Cement

1 Introduction

The cement industry accounts for nearly 8% of global anthropogenic CO_2 emissions, driven primarily by clinker production, while concrete is the second most consumed material worldwide after water. It simultaneously faces accelerated deterioration under changing climatic conditions [1, 2]. This creates a self-reinforcing cycle: greater emissions from cement production intensify climate change, which accelerates concrete degradation and increases demand for new construction. At the regional scale, concrete represents approximately 70% of the Icelandic building stock [3], underscoring the urgency of sustainable production strategies in this context.

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Partially substituting clinker with Supplementary Cementitious Materials (SCMs) is a widely accepted decarbonization pathway [4]. Industrial by-products such as Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) are the most established SCMs, with substitution levels reaching up to 40% [5]. However, their dwindling availability has driven growing interest in natural pozzolans—siliceous or aluminosilicate materials of volcanic origin that react chemically with calcium hydroxide to form cementitious compounds [6]. In the Nordic context, Adediran et al. [7] identified Icelandic volcanic pozzolans (VPI) as a promising and abundant SCM candidate, subsequently confirmed in a comparative evaluation of 15 SCMs in which VPI ranked as high-performing owing to its elevated reactivity and highly amorphous microstructure [7].

Life Cycle Assessment (LCA) is the most comprehensive methodology for evaluating SCM environmental performance across multiple impact categories [8]. The growing literature on volcanic pozzolans consistently demonstrates their technical viability while revealing a critical gap: no study has yet conducted a multi-impact-category LCA of volcanic pozzolans sourced from geographically distinct extraction sites. Existing assessments have been largely limited to global warming potential, neglecting acidification, eutrophication, and resource depletion. The influence of extraction location on environmental profile also remains entirely unexamined, despite the well-documented mineralogical variability of Icelandic volcanic deposits.

To address these gaps, this study conducts a process-based LCA of VPI from three distinct Icelandic sites, with site-specific inventory data. The study aims to: (1) quantify the environmental impacts of VPI production and VPI-blended cement across multiple categories relative to OPC; (2) evaluate the influence of extraction site on environmental performance; and (3) identify, through contribution analysis, the key hotspots driving environmental burdens.

2 Methodology

This study employs process-type LCA (PLCA), following the ISO 14040/14044 framework, encompassing four phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [9].

2.1 Case Study Description

VPI material is extracted from three sites in southern Iceland (Fig. 1): (i) Lambafell (LF), an active quarry transitioning to VPI extraction with an annual capacity of approximately 541,390 t; (ii) Litla Sandfell (LS), a newly identified deposit projected to yield 1.0 Mt./year; and (iii) Landeyjahöfn (LH), an offshore marine sediment site also anticipated to yield approximately 1.0 Mt./year. Centralized processing is conducted at a proposed facility in Þorlákshöfn (TPH). The production mix corresponds to 10% from LF, 23% from LS, and 67% from LH per tonne of VPI. Processing includes freshwater washing of LH material (chloride reduction to <0.1%), sequential ball milling to below 10 μm, and waste-heat-integrated drying.

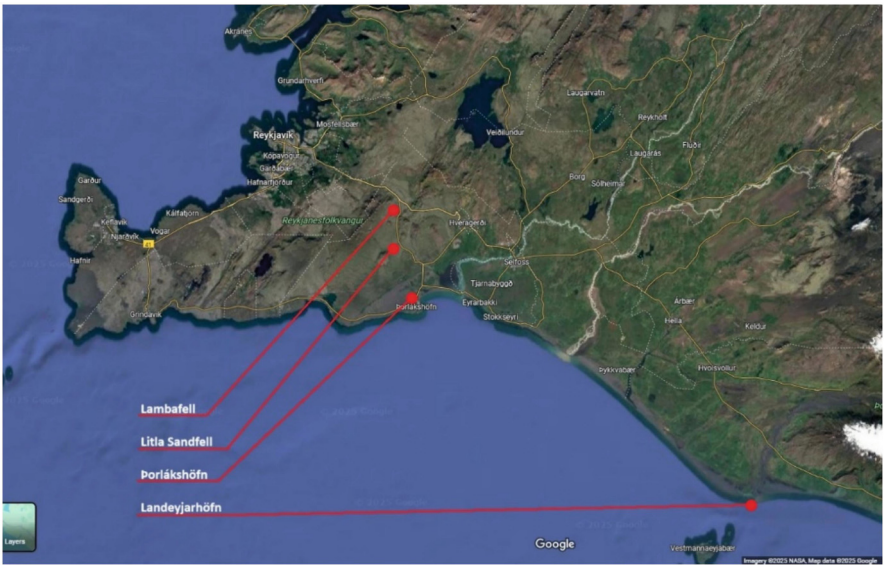


Fig. 1. Geographical distribution of VPI extraction sites and the Þorlákshöfn processing facility.

2.2 Goal, Scope, and Declared Units

The declared unit is one tonne of VPI (cradle-to-gate). System boundaries follow EN 15804 modules A1–A3: raw material extraction (A1), transport to TPH (A2), and centralized processing including washing, grinding, and drying (A3). Where co-products arise, specifically the aggregate by-product at LF (34% by mass) and LS (10% by mass), environmental burdens are allocated on a mass basis in accordance with the ISO 14044 physical allocation hierarchy. This approach is considered appropriate given that VPI constitutes the dominant mass fraction at both sites (66% and 90%, respectively), and that LH, contributing 67% of the total production mix, yields no by-product, rendering allocation irrelevant for the majority of system inputs. Moisture content was assumed to be 30% for LB and LS, and 50% for LH.

2.3 Life Cycle Inventory

Primary inventory data were collected between September 2023 and April 2024 from engineers and project managers at BM Vallá, Hornsteinn, and Heidelberg Materials. LF provided detailed operational data as the only active site; LS and TPH inventories were estimated from anticipated operational parameters. Secondary data were sourced from GaBi (v8.0) and Ecoinvent. Key inventory parameters are summarised in Table 1. The complete process-level inventory, including energy inputs per unit process, is provided as supplementary material at: LCA for the VPI Material.mmap

The mass flow of different processes on the GaBi model is shown on Fig. 2.

Table 1. Key life cycle inventory parameters per production site.

Parameter	LF	LS	TPH (incl. LH)
Material mined (t/yr)	541,390	1,000,000	1,000,000
Diesel (L/yr)	621,308	1,185,000	2,575,000
Electricity (kWh/yr)	–	3,600,000	410,000,000
Water (m^3/yr)	–	–	1,000,000

2.4 Life Cycle Impact Assessment (LCIA)

Environmental impacts were characterised using the ReCiPe 2016 Midpoint (H) method, implemented in GaBi 8.0, covering 10 midpoint impact categories. Results are further interpreted through Environmental Footprint (EF 3.1) normalisation to enable cross-category comparison [10].

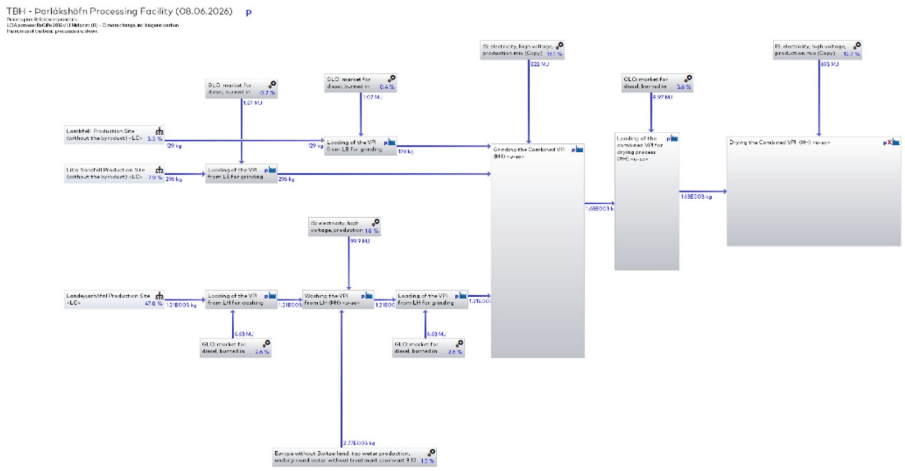


Fig. 2. Mass flow of Production Processes of the VPI Material – GaBi Model.

3 Results

3.1 LCIA Results

The LCIA results are presented in Table 2. The climate change impact of VPI production is 25.5 kg CO_2-eq per tonne of Icelandic Volcanic Pozzolan (VPI) produced. For context, OPC production typically generates 750–900 kg CO_2-eq/t [11], meaning VPI carries approximately 97% lower climate change impact per tonne of material. At an 18% clinker substitution rate, incorporating VPI reduces the carbon intensity of blended

cement from approximately 820 kg CO_2-eq/t (OPC) to approximately 698 kg CO_2-eq/t—a reduction of approximately 15% per tonne of cement binder. Other notable impact categories include Terrestrial Acidification (0.097 kg SO_2-eq), Fossil Resource Depletion (6.79 kg oil-eq), and Land Use (0.235 annual crop eq·yr), all substantially lower than OPC benchmarks.

Table 2. Cradle-to-gate LCIA results (per 1 t of VPI, ReCiPe 2016 Midpoint H).

Impact Category	Value	Unit
Climate Change	2.55E+01	kg CO_2-eq
Stratospheric Ozone Depletion	8.45E−06	kg CFC-11 eq
Photochemical Ozone Formation	1.99E−01	kg NO_n eq
Fine Particulate Matter Formation	4.89E−02	kg PM2.5 eq
Terrestrial Acidification	9.70E−02	kg SO_2 eq
Freshwater Eutrophication	2.38E−03	kg P eq
Marine Eutrophication	3.49E−04	kg N eq
Freshwater Ecotoxicity	1.95E−01	kg 1,4-DCB eq
Fossil Resource Depletion	6.79E+00	kg oil eq
Land Use	2.35E−01	annual crop eq·yr

3.2 Contribution (Hotspot) Analysis

The site-level contribution analysis reveals that LH dominates the climate change impact, accounting for 48.1% of total emissions, attributed entirely to marine dredging, the 70 km sailing distance, and onshore pumping operations. The terrestrial sites contribute comparatively little: LF accounts for 3.1%, of which 71% arises from truck transport to TPH, while LS contributes 8.0%, with 58.6% attributable to its high emissions factor despite the proximity to TPH site (22 km for LF and 16 km for LS). At the process level, grinding (14.19%), drying (12.6%), and diesel-powered loading operations (14.15%) are the next most significant contributors, with washing accounting for a further 2.1%. Together, these findings confirm that the environmental profile of the system is predominantly shaped by the energy and logistics intensity of the LH marine extraction stage rather than by the processing operations at TPH, which benefit substantially from Iceland's near-zero-carbon renewable electricity grid. The site- and process-level contributions are illustrated in Figs. 3 and 4, respectively.

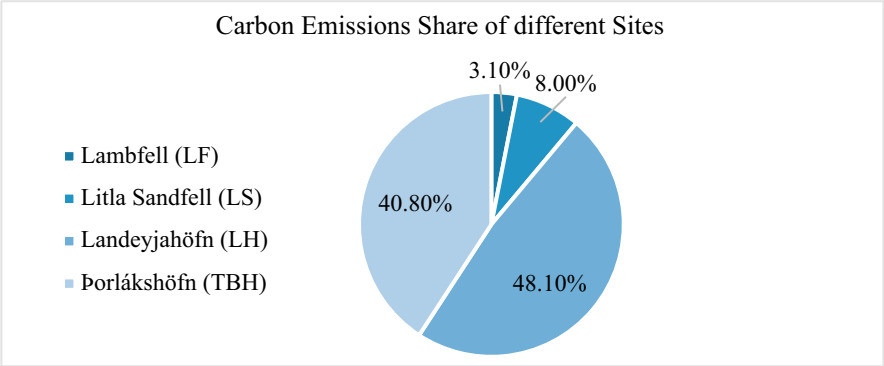


Fig. 3. Site-level contribution to the Climate Change impact category per tonne of VPI produced.

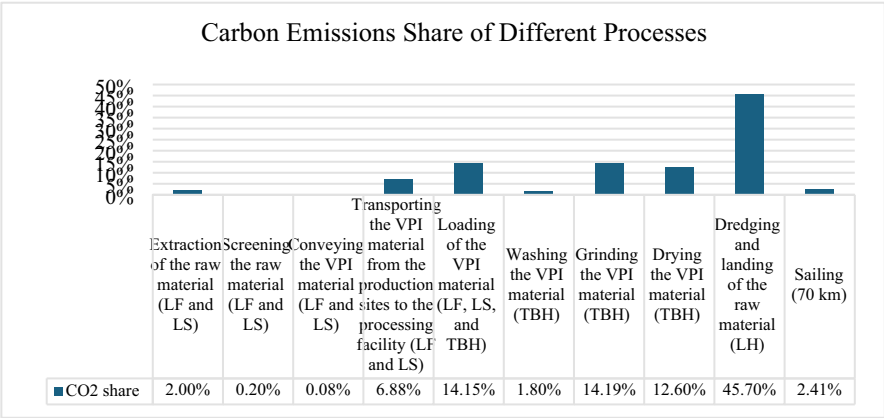


Fig. 4. Process-level contribution to the Climate Change impact category per tonne of VPI produced.

4 Discussion

This study presents the first publicly available, multi-impact-category process LCA of Icelandic volcanic pozzolans, benchmarked across three geographically distinct extraction sites. The result of 25.5 kg CO_2-eq/t reflects the advantageous combination of Iceland's renewable electricity grid and a fully domestic supply chain, firmly establishing VPI as a low-carbon competitive SCM. These findings directly respond to the research gap identified by Liu et al. [12] and Adediran et al. [7], who established the technical merit of volcanic pozzolans in the Nordic context while calling for rigorous environmental assessment. The result also highlights the significant environmental benefit of processing VPI domestically in Iceland compared to exporting raw material for

processing abroad, where fossil fuel-based energy sources and international shipping would substantially increase the overall climate change impact.

Compared to conventional SCMs, VPI is highly competitive. FA typically generates 3–10 kg CO_2-eq/t and GGBFS around 50–80 kg CO_2-eq/t when accounting for full processing impacts, meaning VPI's climate change impact of 25.5 kg CO_2-eq/t falls between these two established alternatives. However, both FA and GGBFS are industrial by-products with limited and declining availability. VPI, by contrast, is an abundant primary resource in Iceland with multi-million-tonne extraction potential, making it a strategically robust alternative independent of industrial supply chains. Importantly, the present study demonstrates that this climate advantage extends to other impact categories—including acidification, eutrophication, and resource depletion—providing a more complete environmental justification for VPI adoption than previously available. The VPI result is also notably lower than the 60 kg CO_2-eq/t reported for volcanic ash sourced from Indonesia and processed for use in Hong Kong by Hossain et al. [13], a difference attributable to Iceland's near-zero-carbon electricity grid and the absence of international shipping in the present system boundary—both structural advantages of domestic Icelandic production that further strengthen the environmental case for VPI.

The dominance of LH marine dredging (48.1% of total climate change impact) is the most actionable finding of this study. It indicates that the overall environmental performance of the system is highly sensitive to the share of LH-sourced material in the production mix and the transportation distance to TPH, which explains the low emissions of LF and LS for their proximity to TPH. Increasing the proportion of terrestrial feedstock from LF and LS, or improving vessel fuel efficiency, would yield the greatest environmental gains. This finding should directly inform production strategy decisions by Heidelberg Materials and associated stakeholders.

Several limitations should be noted. First, inventory data for LS and TPH are based on anticipated rather than measured operational parameters, introducing uncertainty in those estimates. Second, the cradle-to-gate boundary excludes use-phase benefits; a full cradle-to-grave analysis incorporating VPI's service life extension effects would likely strengthen the environmental case further. Third, a formal uncertainty and scenario analysis is planned for the journal version of this work to quantify result variability across all impact categories.

5 Conclusions

This study presents the first publicly available, multi-impact-category process LCA of Icelandic volcanic pozzolans. The principal findings are as follows:

1) VPI production generates 25.5 kg CO_2-eq per tonne (cradle-to-gate), representing approximately 97% lower climate change impact than OPC (750–900 kg CO_2-eq/t), firmly establishing VPI as a low-carbon SCM.
2) VPI carries 49–68% lower climate change impact than GGBFS (50–80 kg CO_2-eq/t), making it highly competitive with the most widely used industrial SCM.
3) VPI's climate change impact is higher than FA (3–10 kg CO_2-eq/t); however, FA is an industrial by-product with declining availability, whereas VPI is an abundant primary resource with multi-million-tonne extraction potential in Iceland.

4) Marine dredging at the LH site accounts for 48.1% of total climate change impact, confirming it as the dominant environmental hotspot and the primary lever for mitigation through production mix optimisation.
5) Grinding (14.19%) and drying (12.6%) are the next largest contributors, reflecting the energy intensity of fine comminution—substantially mitigated by Iceland's near-zero-carbon renewable electricity grid.
6) Domestic processing in Iceland using renewable energy offers a substantial environmental advantage over exporting raw material for processing abroad using fossil fuel-based energy, where international shipping and oil-based drying would increase the climate change impact by an order of magnitude.
7) At an 18% clinker substitution rate, VPI-blended cement carries approximately 15% lower climate change impact than OPC, from ~820 kg CO_2-eq/t to ~698 kg CO_2-eq/t, given VPI's near-negligible carbon footprint of 25.5 kg CO_2-eq/t relative to clinker.

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