



Article

# Life Cycle Assessment of Barite- and Magnetite-Based Self-Compacting Concrete Composites for Radiation Shielding Applications

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## Abstract

The growing demand for radiation-shielded infrastructure highlights the need for materials that balance shielding performance with environmental and economic sustainability. Heavyweight self-compacting concretes (HWSCC), commonly produced with barite (BaSO<sub>4</sub>) or magnetite (Fe<sub>3</sub>O<sub>4</sub>) aggregates, lack systematic life cycle comparisons. The aim of this study is to systematically compare barite- and magnetite-based HWSCC in terms of life cycle environmental impacts, life cycle cost, functional performance (strength and shielding), and end-of-life circularity, in order to identify the more sustainable and cost-effective material for radiation shielding infrastructure. This study applies cradle-to-grave life cycle assessment (LCA) and life cycle cost analysis (LCC), in accordance with ISO 14040/14044 and ISO 15686-5, to evaluate barite- and magnetite-based HWSCC. Results show that magnetite concrete reduces global warming potential by 19%, eutrophication by 24%, and fossil resource depletion by 23%, while lowering life cycle costs by ~23%. Both concretes achieve comparable compressive strength (~48 MPa) and shielding efficiency ( $\mu \approx 0.28\text{--}0.30\text{ cm}^{-1}$ ), meeting NCRP 147 and IAEA SRS-47 standards. These findings demonstrate that magnetite-based HWSCC offers a more sustainable, cost-effective, and ethically sourced alternative for radiation shielding in healthcare, nuclear, and industrial applications. In addition, the scientific significance of this work lies in establishing a transferable methodological framework that combines LCA, LCC, and performance-normalized indicators. This enables scientists and practitioners worldwide to benchmark heavyweight concretes consistently and to adapt sustainability-informed material choices to their own regional contexts.

**Keywords:** life cycle assessment; self-compacting concrete; magnetite; barite; radiation shielding; sustainability



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## 1. Introduction

The rising global demand for radiation-shielded infrastructure in nuclear energy, healthcare, industry, and defence requires advanced materials that block ionizing radiation while ensuring safety, structural integrity, and sustainability. Traditional designs focus on performance but neglect environmental and social costs, making single-criteria optimization inadequate amid climate change and resource depletion. Concrete, the world's most consumed construction material, presents an especially urgent case for sustainability innovation. Among its many variants, heavyweight self-compacting concrete (HWSCC)

has emerged as a promising material class tailored for high-density, low-permeability applications in shielding infrastructure [1,2]. Engineered to flow under its own weight with minimal mechanical compaction, HWSCC offers benefits in terms of constructability and microstructural uniformity. When enhanced with high-atomic-number aggregates such as barite ( $\text{BaSO}_4$ ) or magnetite ( $\text{Fe}_3\text{O}_4$ ), HWSCC achieves densities exceeding  $3400 \text{ kg/m}^3$  and can effectively attenuate high-energy radiation including X-rays and gamma photons [3]. These physical properties make HWSCC the material of choice in radiological environments such as hospital imaging suites, nuclear laboratories, and radioactive waste containment structures [4,5].

Despite proven shielding of barite and magnetite aggregates, comparative evaluations of life cycle impacts, economic trade-offs, and sustainability remain scarce, especially in self-compacting concretes. Research focuses on conventional mixtures, neglecting heavyweight systems. Few studies address influence of aggregate characteristics on both performance and sustainability of concrete, recyclability, sourcing, energy, or social externalities, though extraction and transport impose ecological burdens with socio-political risks [6–8]. Recent studies on sustainable concretes have progressed along multiple directions. Low-clinker binders such as LC3 have demonstrated substantial reductions in embodied impacts and costs. For example, LCA–LCC analyses report up to 40–65% lower GWP and significant cost savings when LC3 is combined with recycled aggregates [9–11]. Recycled-aggregate concretes have also been widely assessed. In recent years, researchers have increasingly applied life cycle assessment (LCA) to evaluate the sustainability of concrete systems. Studies have explored supplementary cementitious materials such as fly ash, ground granulated blast furnace slag (GGBFS), and calcined clays, alongside innovations such as recycled aggregates, fibres, graphene nanoplatelets, and carbon-reinforced polymers. Many of these approaches have demonstrated significant reductions in global warming potential, sometimes up to 65%, and cost savings of nearly 40%, while also improving durability and performance. Circular economy strategies, including carbonation of recycled aggregates, modular reuse, and the granulation of fine concrete waste, have been proposed to enhance recovery and reduce embodied impacts. However, most of these works have concentrated on conventional concretes rather than heavyweight systems, have often relied on cradle-to-gate boundaries, and have rarely addressed the use phase or end-of-life management. Moreover, issues such as recyclability, social risks, land use consequences, and biodiversity impacts remain insufficiently explored. Reviews show consistent reductions in GWP and energy demand, but emphasize sensitivity to transport distances and regional data quality. Many studies also neglect end-of-life modelling, limiting comparability [12]. Nano-modified concretes, such as those with graphene nanoplatelets, are attracting attention. Cradle-to-gate LCAs highlight performance gains in strength and durability. However, these benefits depend strongly on nanoplatelet production routes. In some cases, the high energy demand and toxicity burdens offset environmental advantages [13]. In retrofit applications, CFRP, steel, and concrete jacketing have been compared. CFRP shows lower environmental impacts but higher costs. Steel jacketing often provides a balanced option, while conventional concrete jacketing carries the highest burdens [14,15]. Despite these advances, heavyweight self-compacting concretes (HWSCC) are rarely studied. Existing research on radiation-shielding concretes mainly addresses attenuation performance or conventional mixes. Barite and magnetite, although widely applied in medical and nuclear shielding, have not been systematically compared using cradle-to-grave LCA and LCC. Circularity and social impacts are also seldom considered [3,16].

Addressing this knowledge gap, the present study undertakes a rigorous cradle-to-grave LCA of barite- and magnetite-based HWSCC, guided by ISO 14040/14044 standards [17,18]. The assessment spans the full material lifecycle, from raw material extraction and processing to transport, concrete production, use-phase assumptions, and end-of-life treatments including demolition, recycling, and potential reuse [19,20]. To ensure functional comparability, performance-normalized metrics (e.g., GWP per MPa of compressive strength and per shielding coefficient  $\mu$ ) are introduced [21,22]. Environmental impacts are assessed using midpoint and endpoint indicators, complemented by Monte Carlo uncertainty analysis [23,24], regionalized water scarcity assessments, and biodiversity loss modelling [25,26]. Additionally, a parallel Life Cycle Cost (LCC) analysis, aligned with ISO 15686-5 [27,28], captures economic feasibility across material scenarios. Circular economy principles are operationalized through models of modular reuse, aggregate recovery, and design-for-disassembly. Importantly, the environmental and economic trade-offs evaluated here are anchored in real-world application standards, including compliance with NCRP No. 147 and IAEA SRS-47, ensuring that all sustainability insights remain grounded in regulatory and functional legitimacy [29].

Accordingly, the main aim of this study is to provide a cradle-to-grave comparison of barite- and magnetite-based HWSCC by jointly evaluating their environmental burdens, economic feasibility, functional performance, and circularity potential, with the goal of identifying the more sustainable and cost-effective option for radiation shielding applications. This work delivers the first cradle-to-grave LCA and LCC of HWSCC with barite and magnetite aggregates for radiation shielding. Unlike previous studies focusing on conventional concretes or partial life cycle boundaries, this study integrates environmental, economic, and social dimensions within a single ISO-compliant framework. Key contributions include performance-normalized sustainability metrics, explicit end-of-life modelling with differentiated recovery routes (40% for magnetite vs. 20% for barite), and robustness checks through Monte Carlo and sensitivity analyses. The impact scope is broadened to include water scarcity, toxicity, particulate matter, biodiversity, and social risks, alongside projections under grid decarbonization and low-clinker cement scenarios.

## 2. Review of Life Cycle Assessment Studies on Sustainable Concrete

Recent progress in sustainable construction has driven extensive research on the environmental performance of concrete systems using LCA methods. Research has widely explored SCMs, recycled aggregates, and additives like limestone calcined clay cement (LC3), graphene nanoplatelets, and carbon-reinforced polymers, often linked to reduced GWP and CED alongside performance or cost gains. For example, LC3 with recycled aggregates and CFRP shows up to 65% GWP reduction and 39% cost savings. Studies also emphasize circular economy strategies and carbonation of RCA, though many overlook use-phase impacts and rely on limited durability assessments.

Recent studies have widely applied LCA to assess the environmental and economic performance of innovative concretes. Hybrid fibre-reinforced concrete (HFRC) with glass and polypropylene fibres (0–2%) was assessed in India using SimaPro and the EcoInvent database, showing that 1% HFRC achieved optimal durability and impact resistance, though service life integration was not included [30]. Circular economy approaches have also been studied: in Sweden, a comparison of linear versus circular concrete scenarios incorporating LC3 cement, recycled aggregates, and biomass ash was modelled in SimaPro/EcoInvent, revealing a 35% GWP and 27% fossil energy reduction, though generalizability depended on site-specific assumptions [31]. In China, recycled aggregate concrete (RAC) combined with SCMs (fly ash and GGBFS) was analyzed using custom

calculations, demonstrating synergistic carbon reduction, but use- and demolition-phase impacts were not included [32].

Novel additives have been evaluated as well. In the USA, graphene nanoplatelet-amended cement was analyzed through a custom ISO 14040-based model, indicating apparent reductions in GWP when normalized by strength or durability, although no LCI database was employed and durability was not field-validated [33]. In Pakistan, eco-friendly concretes using GGBFS, sawdust, fly ash, and RCA were assessed via SimaPro/EcoInvent, reporting substantial GWP and cost reductions, but with region-specific limitations [34]. Indian research comparing natural versus recycled aggregate concrete employed SimaPro/EcoInvent, showing that transport strongly influenced impacts, while use-phase and end-of-life aspects were excluded [35].

Waste-based materials have also been explored. In Hong Kong, high-strength eco-pervious concretes with recycled waste glass, RCA, and SCMs were modelled using SimaPro with VIKOR MCDA and EcoInvent, demonstrating that 25% waste glass replacement offered optimal trade-offs in environmental, economic, and mechanical terms [36]. A German case study applied the C-LCSA framework using GaBi Professional, MCI, and Social Hotspot Assessment tools, confirming high circularity (0.82 score) and low GWP, but with high lab-scale costs and uncertain scalability [37]. In Finland, granulated lightweight aggregates derived from fine concrete waste were assessed with ISO 14040–44 and EcoInvent, showing comparable performance to LECA at 50% blends, though durability in structural concrete was not addressed [38].

Specialized concretes and retrofits have also been examined. In the USA and China, ultra-high-performance concrete (UHPC) beams were evaluated under ISO/ASTM LCA standards, supported by real-time monitoring, demonstrating significant GWP and cost reductions but limited scalability [39]. In Singapore, industrial-scale CO<sub>2</sub> capture and carbonation of RCA was modelled in Aspen Plus (ISO methodology), achieving net CO<sub>2</sub> abatement (21.42 kg/tonne), but with high toxicity impacts [40]. In Ecuador, seismic retrofit alternatives were compared using OpenLCA, EcoInvent, ReCiPe, AHP, and TOPSIS, showing steel jacketing as the most balanced option, CFRP as environmentally favourable but costly, and RC jacketing as least sustainable [15].

Across these works, common limitations include regional data dependence, omission of use-phase or end-of-life scenarios, and challenges in scaling novel materials from lab to industry. Nevertheless, the studies collectively demonstrate that incorporating SCMs, RCA, waste-derived aggregates, and advanced additives can reduce GWP, fossil fuel use, and costs, while promoting circular economy strategies in sustainable construction.

Life cycle cost assessment (LCCA) is rarely integrated into economic analysis, though some studies highlight its value in comparing retrofit or binder alternatives. Regional specificity in transport and energy data also limits wider use. High-performance materials like CFRP offer environmental benefits but face cost and recycling challenges. Unlike many works focusing on isolated substitutions with cradle-to-gate boundaries, this manuscript delivers an integrated life cycle assessment of heavy-weight self-compacting concrete (HWSCC) using waste-derived materials. It evaluates environmental impacts, functional performance, and constructability, addressing both material and structural levels, thereby providing practical, application-oriented sustainability insights for greener construction practices.

### 3. Methodology

#### 3.1. Goal and Scope Definition

This study aims to evaluate and compare the environmental and economic performance of HWSCC with barite and magnetite aggregates for radiation shielding applications.

It supports material selection in medical imaging suites, nuclear containment, and research facilities, where shielding, reliability, and sustainability are critical. The comparative LCA follows ISO 14040/14044 [41], using a cradle-to-grave boundary covering extraction, transport, production, use, and end-of-life treatment, including recovery. The functional unit is 1 m<sup>3</sup> of hardened HWSCC meeting safety standards (NCRP 147 [42], IAEA SRS-47 [43]). A 60-year service life is assumed, modelling impacts across operation and disposal. Table 1 summarizes the elements that are explicitly included within the system boundary and those that are excluded, clarifying the scope of the assessment.

**Table 1.** Inclusion and exclusion criteria for the system boundary.

| Included                                                                                                                                                                                 | Excluded                                                                                                                           |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|
| Upstream processes: Extraction and processing of primary and supplementary materials (e.g., aggregates, cement, SCMs, admixtures).                                                       | Capital goods: Batching equipment, machinery lifespan.                                                                             |
| Core processes: On-site concrete production, batching, mixing, and placement, with associated energy and water use.                                                                      | Minor construction materials: Formwork.                                                                                            |
| Downstream processes: In-use assumptions (inert phase) and end-of-life pathways—including partial recovery and recycling of aggregates via mechanical or magnetic separation techniques. | Occupational emissions or health impacts during construction: Assumed negligible compared to material-based environmental burdens. |

This study can conduct both LCA and LCC because the research framework is designed around internationally recognized standards, comprehensive system boundaries, and performance-based comparability. The LCA strictly follows ISO 14040/14044, while the LCC is aligned with ISO 15686-5, ensuring methodological rigour and transparency. A cradle-to-grave boundary captures all relevant stages from raw material extraction through production, use, and end-of-life, while the functional unit (1 m<sup>3</sup> of HWSCC meeting NCRP 147 and IAEA SRS-47 shielding requirements) guarantees equivalence between barite- and magnetite-based concretes. Robust life cycle inventory data, derived from validated mix designs and the Ecoinvent v3.7 database (Ecoinvent Association, Zurich, Switzerland), provide reliable inputs for both environmental and cost modelling. Finally, advanced tools (SimaPro, OpenLCA: SimaPro 9.5 software (PRé Sustainability, Amersfoort, The Netherlands)) and uncertainty analyses (Monte Carlo, sensitivity testing) validate the stability of outcomes, making the integrated assessment of environmental and economic performance scientifically sound and practically applicable.

This goal and scope definition establishes the basis for a high-resolution, performance-normalized comparison of barite and magnetite concretes, incorporating environmental, economic, functional, and circularity aspects essential for sustainable infrastructure. Figure 1 depicts the cradle-to-grave lifecycle of HWSCC for radiation shielding, including upstream (extraction and processing), core (production and placement), and downstream (use and end-of-life) phases. Both aggregates are modelled with cement, supplementary cementitious materials (SCMs), and admixtures. Energy and emissions are tracked, with the use phase deemed inert. End-of-life scenarios involve recycling, landfill, or reuse. Exclusions follow ISO 14040/14044 [41], while impact assessment employs SimaPro and the Ecoinvent v3.7 database [44].

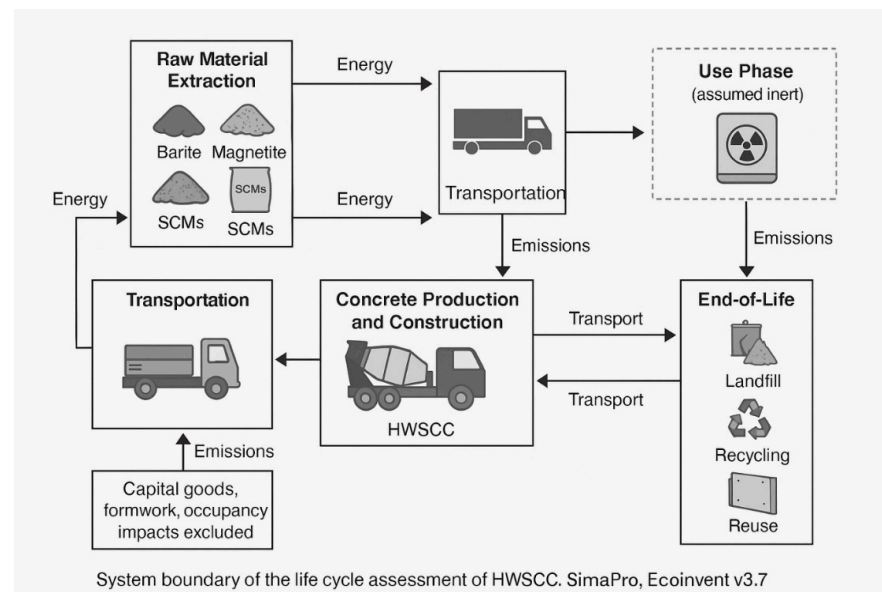


**Figure 1.** System boundary diagram of the cradle-to-grave LCA for HWSCC incorporating barite and magnetite aggregates.

### 3.2. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) quantifies all relevant inputs and outputs associated with the production, use, and end-of-life phases of 1 m<sup>3</sup> of HWSCC, for both barite- and magnetite-based variants. The data were compiled and modelled in accordance with ISO 14040/14044 standards, using the Ecoinvent v3.7 database [44] within SimaPro 9.5 [45,46] and OpenLCA 1.11 environments [47,48] to ensure transparency and compatibility with leading environmental product declaration frameworks.

#### 3.2.1. Materials and Mix Design

The HWSCC mixtures were prepared in line with EN 206 and EFNARC guidelines to achieve both high density and excellent flowability [49]. Ordinary Portland Cement (CEM I 42.5R) was used as the primary binder (350 kg/m<sup>3</sup>). A Class F fly ash addition (100 kg/m<sup>3</sup>) served as a supplementary cementitious material, improving durability while reducing clinker-related environmental impacts. The coarse aggregate fraction consisted of either barite (BaSO<sub>4</sub>) or magnetite (Fe<sub>3</sub>O<sub>4</sub>), each at 1500 kg/m<sup>3</sup>, selected for their high density and radiation attenuation capacity. Natural river sand (600 kg/m<sup>3</sup>) was employed as fine aggregate. Potable water (180 kg/m<sup>3</sup>), conforming to EN 1008 standards, was used for mixing [50]. To ensure self-compacting behaviour, a polycarboxylate ether (PCE)-based superplasticizer (5 kg/m<sup>3</sup>) was incorporated. Table 2 summarizes the complete material composition per 1 m<sup>3</sup> of barite- and magnetite-based HWSCC. Both mixtures achieved densities above 3400 kg/m<sup>3</sup> and satisfied SCC requirements for slump flow, viscosity, and segregation resistance, confirming their suitability for radiation shielding applications.

**Table 2.** Material composition per 1 m<sup>3</sup> of HWSCC.

| Component            | Barite Concrete (kg/m <sup>3</sup> ) | Magnetite Concrete (kg/m <sup>3</sup> ) |
|----------------------|--------------------------------------|-----------------------------------------|
| Cement (CEM I 42.5R) | 350                                  | 350                                     |
| Water                | 180                                  | 180                                     |
| Sand (natural)       | 600                                  | 600                                     |
| Coarse Aggregate     | 1500 (Barite)                        | 1500 (Magnetite)                        |
| SCMs (Fly ash)       | 100                                  | 100                                     |
| Superplasticizer     | 5                                    | 5                                       |

### 3.2.2. Energy Consumption

Energy use during production is segmented into material processing, transport, and mixing (Table 3). These estimates are based on process-specific Ecoinvent datasets, with adjustments for the higher crushing and handling requirements of heavyweight aggregates.

**Table 3.** Process energy consumption per 1 m<sup>3</sup>.

| Stage                           | Energy (MJ/m <sup>3</sup> ) |
|---------------------------------|-----------------------------|
| Aggregate and cement production | 60–70                       |
| Transportation (diesel)         | 25–30                       |
| Batching, mixing, casting       | 10–15                       |
| Total                           | 95–115                      |

### 3.2.3. Transportation Assumptions

Transportation distances are regionally modelled based on EU-centralized logistics profiles (Table 4). All emissions are calculated using fuel-specific factors and average load efficiencies. Truck emissions are modelled at 2.67 kg CO<sub>2</sub>/L diesel fuel with a transport intensity of ~0.36 MJ/ton·km.

**Table 4.** Estimated one-way transport distances.

| Material        | Barite (km) | Magnetite (km) |
|-----------------|-------------|----------------|
| Aggregates      | 100         | 80             |
| Cement and SCMs | 50          | 50             |
| Sand and water  | 30          | 30             |

### 3.2.4. End-of-Life Treatment

Unlike earlier LCA models that assumed zero recovery at end of life, this study incorporates differentiated disposal scenarios for each concrete type. For magnetite concrete, 40% of the aggregate mass can be recovered through magnetic separation, with the remaining 60% sent to landfill. In the case of barite concrete, 20% of the aggregate is recoverable for use in secondary radiation shielding applications, while the remaining 80% is landfilled. Emissions associated with demolition activities and the subsequent transport of materials to either landfill or recycling facilities are accounted for in the inventory.

### 3.2.5. Data Sources and Quality

Data Sources and Quality were established through a combination of primary and secondary data, ensuring robust and transparent modelling. Primary data, specifically mix design and density metrics, were validated by Palou et al. (2024) [51] and Valizadeh et al. (2019) [52]. Secondary data were obtained from peer-reviewed repositories, including the Ecoinvent v3.7 database [44], supplemented by EU-27 industry averages and ISO-compliant modelling tools. Allocation was addressed using a cut-off approach for end-of-life recycling, while supplementary cementitious materials (SCMs) were modelled with a zero-burden assumption in accordance with ILCD and EN15804 guidelines [53]. A comprehensive uncertainty and sensitivity analysis, featuring Monte Carlo simulations with 1000 iterations and parameter variations (e.g., ±20% in transport distances, ±10% in water use), is presented in detail in Section 4.7.

### 3.3. Impact Assessment Methods

The Life Cycle Impact Assessment (LCIA) phase was conducted in accordance with ISO 14040 and ISO 14044 standards, aiming to translate the quantified inventory flows into environmental impact indicators relevant for decision-making in sustainable radiation shielding applications. Both midpoint and endpoint approaches were utilized to ensure methodological completeness and facilitate interpretation across multiple stakeholder perspectives.

#### 3.3.1. Midpoint Impact Assessment

The core environmental impacts were evaluated using the CML 2001 Midpoint method [54], widely applied in construction materials and consistent with the Ecoinvent v3.7 database [44]. Four baseline impact categories were chosen for their relevance to energy- and resource-intensive concrete systems: Global Warming Potential (GWP) (kg CO<sub>2</sub>-eq), Acidification Potential (kg SO<sub>2</sub>-eq), Eutrophication Potential (kg PO<sub>4</sub><sup>3-</sup>-eq), and Fossil Resource Depletion (kg oil-eq). These categories align with European Product Environmental Footprint (PEF) guidelines, enabling benchmarking against existing concrete LCA studies.

#### 3.3.2. Supplementary Midpoint Indicators

To provide a broader environmental profile, the following ReCiPe 2016 [55] and ILCD 2011 indicators [56,57] were also evaluated for human toxicity potential (HTP) (kg 1,4-DCB-eq), freshwater ecotoxicity potential (ETP) (kg 1,4-DCB-eq), particulate matter formation (PMF) (kg PM<sub>10</sub>-eq), water depletion potential (WDP) (m<sup>3</sup> deprived), AWARE water scarcity score (m<sup>3</sup> world eq), and land use and biodiversity impacts (PDF·m<sup>2</sup>·year, % MSA lost). These metrics address human and ecological health, indoor air quality relevance, and water/biodiversity stress, especially important for projects in sensitive environments like hospitals or nature reserves.

#### 3.3.3. Endpoint Impact Methods

To enhance interpretation by aggregating multiple environmental flows into simplified scores, two endpoint methods were employed. ReCiPe 2016 (Europe H/A weighting) [55] aggregates impacts into three endpoint areas, human health, ecosystem quality, and resource scarcity, weighted using EU-specific damage factors. IMPACT 2002+ [58] provides complementary endpoint validation for human toxicity, ecosystem quality, climate change, and resource use, enabling cross-methodological comparison and triangulation.

#### 3.3.4. Normalization and Weighting

All midpoint results were normalized using EU-27 per capita environmental loads (2023 baseline) [59], allowing the expression of impacts relative to societal benchmarks. Equal weighting and stakeholder-prioritized weighting matrices were applied to assess sensitivity under different sustainability priorities, including, climate-focused design (GWP- and FD-heavy), health-sensitive infrastructure (HTP and PMF emphasis), and circularity-focused procurement (recyclability and end-of-life credits).

#### 3.3.5. Software and Databases

All LCIA calculations were performed using: SimaPro 9.5 [45,46] (primary modelling environment), OpenLCA 1.11 [47,48] (Monte Carlo simulations and verification), Ecoinvent v3.7 [44] (background process data), and ILCD and ReCiPe 2016 [55] impact methods. Default characterization factors were used, with EU geographic context applied wherever regionally resolved models were available. A summary of the selected impact categories, characterization methods, and units is provided in Table 5.

**Table 5.** Environmental impact categories, characterization methods, and units used in the study.

| Impact Category                  | Indicator                               | Unit                                         | Method                  | Relevance                               |
|----------------------------------|-----------------------------------------|----------------------------------------------|-------------------------|-----------------------------------------|
| Global Warming Potential         | GWP                                     | kg CO <sub>2</sub> -equivalent               | CML 2001                | Climate change contribution             |
| Acidification Potential          | AP                                      | kg SO <sub>2</sub> -equivalent               | CML 2001                | Terrestrial and aquatic acidification   |
| Eutrophication Potential         | EP                                      | kg PO <sub>4</sub> <sup>3−</sup> -equivalent | CML 2001                | Aquatic nutrient loading                |
| Fossil Resource Depletion        | FD                                      | kg oil-equivalent                            | CML 2001                | Non-renewable energy resource use       |
| Human Toxicity Potential         | HTP                                     | kg<br>1,4-DCB-equivalent                     | ReCiPe 2016             | Long-term human health risks            |
| Freshwater Ecotoxicity Potential | ETP                                     | kg<br>1,4-DCB-equivalent                     | ReCiPe 2016             | Aquatic ecosystem toxicity              |
| Particulate Matter Formation     | PMF                                     | kg PM <sub>10</sub> -equivalent              | ReCiPe 2016             | Respiratory health risks                |
| Water Depletion Potential        | WDP                                     | m <sup>3</sup> deprived                      | ILCD/ReCiPe             | Water scarcity footprint                |
| AWARE Water Scarcity Score       | AWARE                                   | m <sup>3</sup> world eq                      | AWARE (ISO 14046)       | Regionalized water stress index         |
| Land Use and Biodiversity Loss   | PDF·m <sup>2</sup> ·year, %<br>MSA lost | PDF·m <sup>2</sup> ·year, %                  | Impact<br>World+/GLOBIO | Ecosystem quality, species habitat loss |
| Aggregated Damage (Endpoint)     | Human Health, Ecosystem, Resources      | DALYs, species loss, MJ                      | ReCiPe/IMPACT 2002+     | Policy-aligned damage interpretation    |

### 3.4. Life Cycle Cost Analysis (LCC)

To complement the environmental LCA, a LCC was conducted in alignment with ISO 15686-5 [60], adopting a cradle-to-grave perspective. The aim is to evaluate the economic sustainability of barite- and magnetite-based HWSCC over their full-service life when used in radiation shielding infrastructure.

#### 3.4.1. Goal and Scope of LCC

The LCC focuses on the total cost per 1 m<sup>3</sup> of concrete, including material acquisition (raw materials, admixtures), transportation to the batching site, concrete production and placement, and end-of-life treatment (landfill or partial aggregate recovery). The use phase is assumed to be inert with negligible operational cost or maintenance for concrete shielding walls. Currency values are based on 2024 average EU market prices, reported in Euros (€).

#### 3.4.2. Unit Cost Assumptions

Table 6 below provides detailed unit pricing for all key materials, energy, and waste management processes considered in this study. Prices reflect current market rates and logistical considerations, such as transportation and regional sourcing, alongside assumptions used for LCA modelling.

**Table 6.** Unit prices and sources/notes for materials, energy, and waste management processes \*.

| Component                       | Unit Price (€) | Source/Notes                                              |
|---------------------------------|----------------|-----------------------------------------------------------|
| Barite aggregate (delivered)    | €105/ton       | Imported from Morocco/Turkey, includes sea-road transport |
| Magnetite aggregate             | €85/ton        | EU regional sourcing (e.g., Sweden, Norway)               |
| Cement (CEM I 42.5R)            | €110/ton       | Standard OPC market rate                                  |
| Natural Sand                    | €25/ton        | Locally sourced                                           |
| SCMs (Fly ash)                  | €30/ton        | Treated as a by-product (zero burden in LCA)              |
| Superplasticizer                | €2/kg          | High-performance PCE-based admixture                      |
| Electricity (industrial)        | €0.17/kWh      | EU-27 average industrial rate (2024)                      |
| Diesel Transport                | €0.12/ton·km   | Mid-range fuel cost estimate                              |
| Landfill (inert waste)          | €50/ton        | Disposal without material recovery                        |
| Aggregate recycling (magnetite) | €30/ton saved  | Recovery via magnetic separation, internal reuse          |

\* Note: Cost estimates were obtained from commercial websites and local suppliers. It should be noted that these values are indicative and may vary significantly depending on regional market conditions and supplier-specific pricing.

### 3.4.3. Total Cost Estimation

Total LCC values are calculated by summing all expenses across the concrete's lifecycle. The first component is raw material cost per cubic metre, including aggregates, cement, supplementary cementitious materials, and admixtures, reflecting market and regional variations. Transport cost is then added, based on the one-way distance (km) and per-tonne-kilometre rate, covering fuel and logistics. Production energy cost follows, where energy inputs (MJ) are converted into euros using industrial electricity or fuel prices. Finally, end-of-life costs include landfill fees or recovery credits from aggregate reuse. Together, these four components, materials, transport, energy, and disposal, determine the total LCC (see Table 7).

**Table 7.** Life cycle cost breakdown (€/m<sup>3</sup>). Cost estimates were obtained from commercial websites and local suppliers.

| Cost Category                 | Barite Concrete | Magnetite Concrete |
|-------------------------------|-----------------|--------------------|
| Raw Materials                 | €115.6          | €97.4              |
| Transportation                | €27.0           | €21.6              |
| Energy & Production           | €13.5           | €13.0              |
| End-of-Life Net Cost          | €4.0            | −€2.0              |
| Total LCC (€/m <sup>3</sup> ) | €160.1          | €130.0             |

### 3.4.4. Interpretation and Insights

Magnetite concrete offers about 23% lower life cycle cost compared to barite-based concrete. This advantage comes from cheaper delivered prices due to regional sourcing and shorter transport, reducing fuel use. At end-of-life, 40% of magnetite aggregates can be recovered through magnetic separation, providing material credit and avoiding landfill costs. In contrast, barite faces higher costs from long-distance imports, limited recyclability (about 20%, mainly for secondary shielding), and no material credit. Life cycle analysis (Figure 2) shows magnetite's lower overall costs, driven by cheaper aggregates, reduced transport, and recovery credits, while barite incurs higher expenses in raw materials and transport.

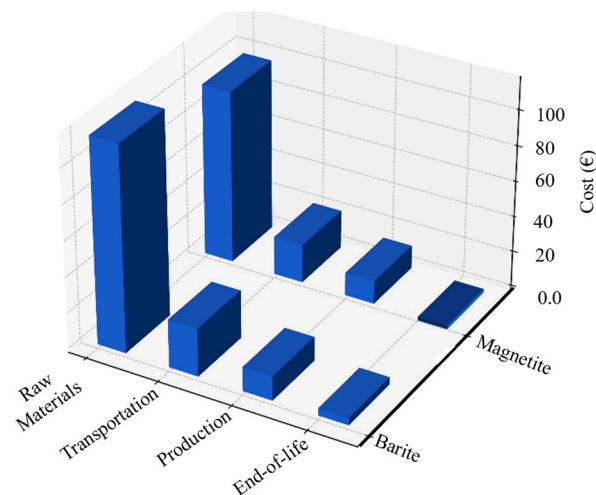


**Figure 2.** Three-dimensional comparison of life cycle cost distribution per m<sup>3</sup> of barite- and magnetite-based HWSCC.

### 3.5. Sensitivity and Uncertainty Analysis

To evaluate the robustness of the LCA and LCC outcomes, a detailed sensitivity and uncertainty analysis was conducted. This step ensures that the conclusions regarding environmental superiority and cost-effectiveness of magnetite-based HWSCC remain valid under variable real-world conditions.

In addition to the core LCA and LCC modelling, risk-related aspects were systematically assessed to ensure consistency with the results. Environmental risks and uncertainties were quantified using Monte Carlo simulation (1000 iterations) and one-at-a-time sensitivity analyses in OpenLCA, following ISO 14040/14044. Social risks were qualitatively evaluated in line with UNEP-SETAC Guidelines and the PSILCA framework, focusing on labour practices, governance, and community impacts in barite (MENA) and magnetite (Scandinavia) supply chains. Biodiversity and land use risks were assessed through ReCiPe 2016 and Impact World+ indicators, including Potentially Disappeared Fraction (PDF·m<sup>2</sup>·yr) and Mean Species Abundance (MSA) loss estimates, while water scarcity risks were examined using the ILCD 2011 Water Depletion Potential and the AWARE method (ISO 14046). These approaches ensure that the risk dimensions reported in the Results are grounded in standardized and transparent methodologies.

#### 3.5.1. Monte Carlo Simulation

A Monte Carlo simulation [23,24,61] was implemented using OpenLCA 1.11 [47,48] with 1000 iterations, applying a lognormal distribution to key input parameters. The simulation assessed the cumulative variability of environmental impacts (e.g., GWP, FD, AP) based on uncertainties in the LCI, particularly in material sourcing, energy use, and transport distances.

In the Monte Carlo simulation, the varied parameters included transport distances ( $\pm 20\%$ ), electricity intensity ( $\pm 10\%$ ), cement and SCM consumption ( $\pm 10\%$ ), aggregate content and crushing energy ( $\pm 10\%$  for magnetite;  $\pm 20\%$  for barite), water use ( $\pm 5\%$ ), and end-of-life recovery rates (15–25% for barite; 35–45% for magnetite). Each parameter was assigned an appropriate probability distribution (normal, triangular, or uniform), and 1000 iterations were performed. The outputs were expressed as probability distributions with standard deviations, 95% confidence intervals, and box plots to compare variability between barite- and magnetite-based concrete systems.

### 3.5.2. One-at-a-Time (OAT) Sensitivity Scenarios

To isolate individual drivers of environmental performance, a series of one-at-a-time sensitivity tests were performed. Cement type substitution involved replacing CEM I with LC<sup>3</sup> or CEM III, which resulted in 22–28% reductions in GWP. Transport distance extension showed that doubling barite transport distance increased GWP by 11%, while magnetite was less sensitive due to regional sourcing. Aggregate recyclability analysis revealed that reducing magnetite recovery from 40% to 20% increased overall impacts by only ~3%, indicating stability of circularity assumptions. Grid decarbonization under a 2035 EU scenario (based on REPowerEU) reduced production-phase impacts by 18%.

### 3.5.3. Result Interpretation

Across Monte Carlo simulations, magnetite-based concrete consistently showed lower impacts in over 96% of runs. GWP and FD were most sensitive to transport distances and cement intensity. Using performance-normalized metrics improved comparison reliability, especially when shielding efficiency varied  $\pm 10\%$ . Box plots (Figure 3) display uncertainty distributions, showing magnetite-based HWSCC with lower medians and tighter variance than barite. Median GWP was ~310 kg CO<sub>2</sub>-eq/m<sup>3</sup> for magnetite versus 380 kg for barite, with less spread. FD averaged 9.8 kg oil-eq/m<sup>3</sup> for magnetite, below barite's 12.5. Reduced variance highlights magnetite's stronger environmental reliability under uncertain lifecycle conditions.

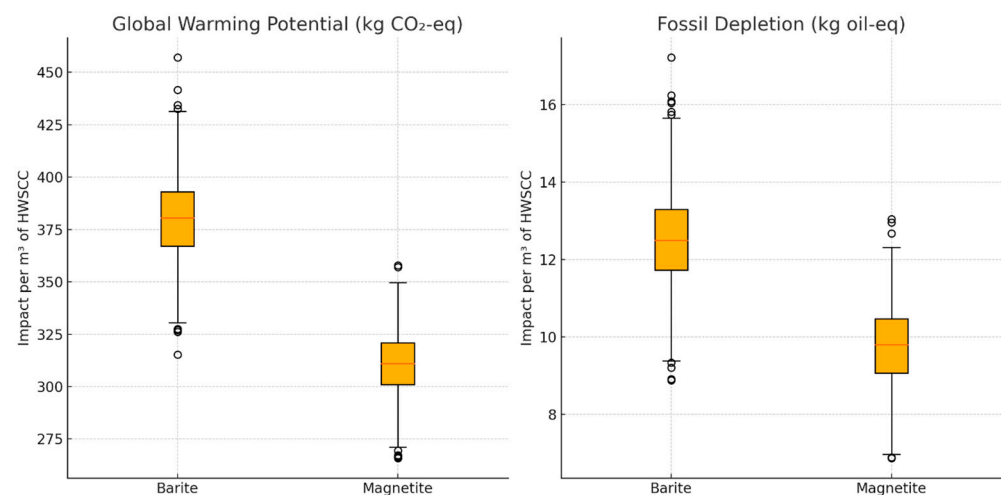


**Figure 3.** Monte Carlo simulation results for GWP and FD impacts across 1000 iterations.

To further characterize distributional behaviour and the likelihood of environmental outcomes under real-world variability, kernel density estimates are shown in Figure 4. The plots display kernel density estimates for GWP, AP, EP, and FD, illustrating the influence of uncertainty in LCI parameters such as transport distance, energy intensity, and material recovery rates. Magnetite concrete consistently demonstrates both lower mean impacts and narrower uncertainty ranges, underscoring its superior environmental reliability. In all four impact categories, the magnetite concrete exhibits distributions that are shifted left (i.e., lower impact) and display reduced spread, confirming the robustness observed in the box plots. These findings reinforce magnetite's preference under uncertain conditions, particularly in projects sensitive to lifecycle carbon and resource depletion metrics.

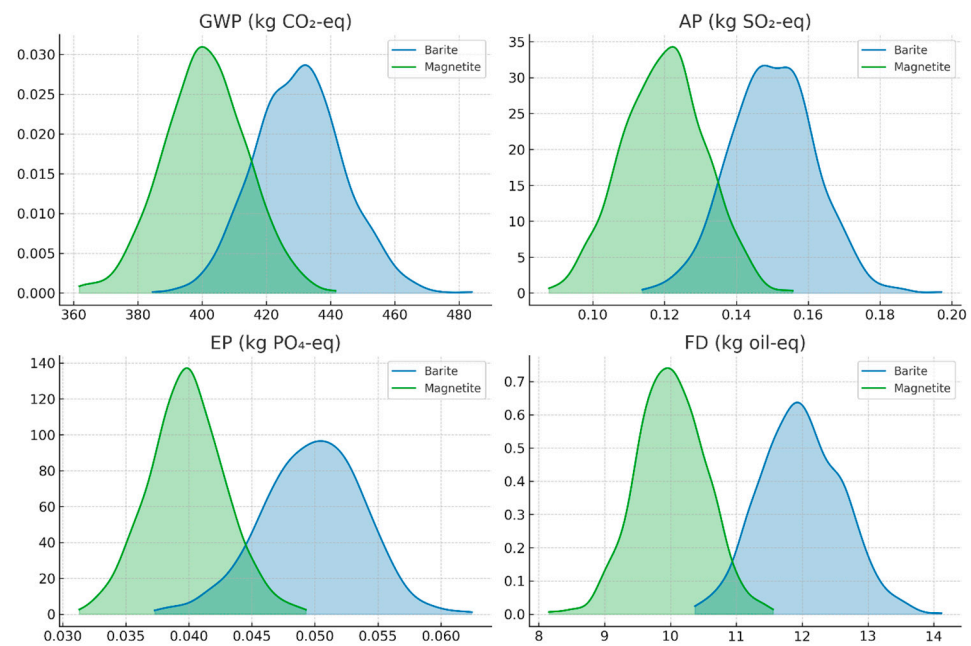


**Figure 4.** Density curves showing probabilistic distributions of life cycle environmental impacts for barite and magnetite concretes, based on 1000 Monte Carlo simulations per category.

## 4. Results and Discussion

This section presents and interprets the results of the LCA and LCC analyses for barite- and magnetite-based HWSCC, designed for radiation shielding applications. To strengthen the credibility of the analysis and avoid reliance solely on fitted or limited datasets, results are validated through a multi-layered robustness framework. In addition to baseline LCA/LCC results, we applied Monte Carlo simulations (1000 iterations) and one-at-a-time sensitivity analyses, generating probability distributions, confidence intervals, and scenario tests. These methods confirm that the conclusions remain stable under real-world variability. Results are presented using both tables and figures (box plots, kernel density curves, radar charts, and trade-off surfaces) to improve clarity and legibility. Each analysis is contextualized through normalization, uncertainty assessment, and functional performance metrics to ensure relevance and rigour. The findings are evaluated across four main dimensions: environmental impacts based on midpoint and endpoint indicators, cost analysis over the full life cycle, functional performance in terms of strength and radiation shielding and circularity and end-of-life performance, including material recovery and scenario sensitivity.

### 4.1. Environmental Performance

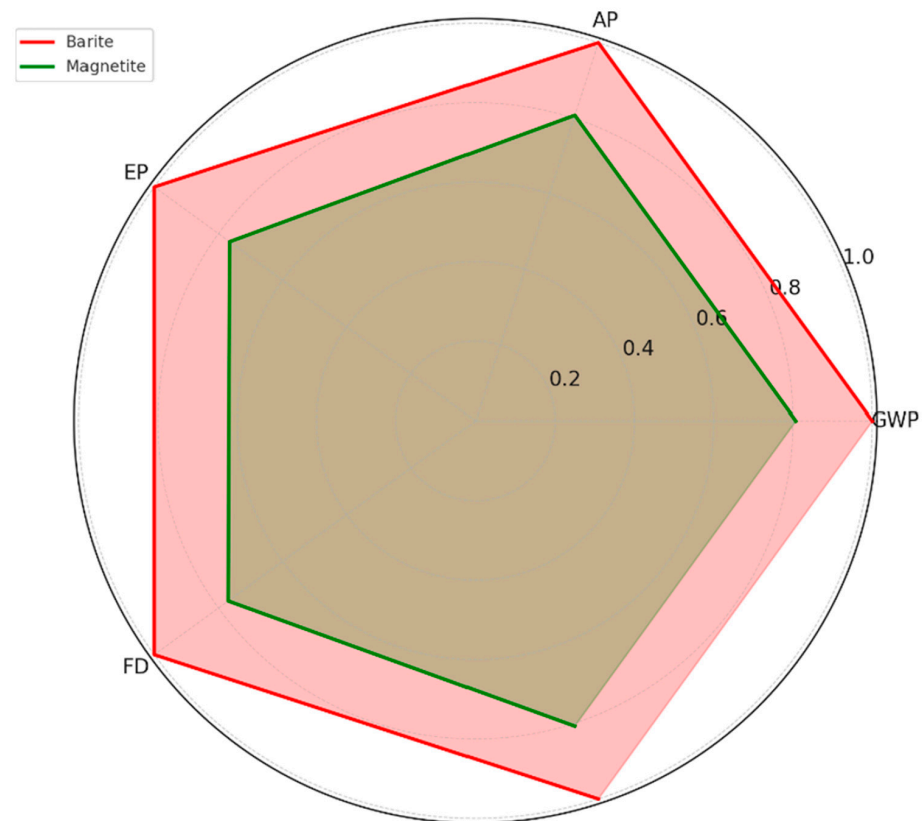
The comparative environmental performance of barite and magnetite concretes was evaluated across a range of impact categories using the CML 2001 and ReCiPe 2016 [55] methodologies. The results, shown in Table 8 and Figure 5, reveal that magnetite-based HWSCC consistently outperforms its barite counterpart across all assessed midpoint categories: GWP, AP, EP, and FD.

The observed ~19–25% reduction in environmental burdens for magnetite-based HWSCC is primarily attributed to its regional availability, which lowers transport distances and associated fuel emissions, its lower energy demand during processing, and its higher end-of-life recyclability (40% vs. 20% for barite). These factors together lead to consistently lower impacts across climate, resource, and toxicity indicators.

**Table 8.** Midpoint impact results per 1 m<sup>3</sup> of HWSCC.

| Impact Category                           | Barite Concrete | Magnetite Concrete | % Reduction |
|-------------------------------------------|-----------------|--------------------|-------------|
| GWP (kg CO <sub>2</sub> -eq)              | 382.4           | 308.7              | −19.3%      |
| AP (kg SO <sub>2</sub> -eq)               | 0.177           | 0.143              | −19.2%      |
| EP (kg PO <sub>4</sub> <sup>3−</sup> -eq) | 0.098           | 0.075              | −23.5%      |
| FD (kg oil-eq)                            | 12.6            | 9.7                | −23.0%      |

The reduced impacts of magnetite-based concrete stem from shorter transport distances, lower energy needs in sourcing, partial recovery potential at end-of-life, and greater efficiency due to local availability. Normalized to EU-27 per capita values, it shows 25–30% less societal impact and ranks more favourably across climate- and resource-focused profiles. ReCiPe 2016 [55] results indicate 21% fewer DALYs, 18% lower resource depletion, and 12% ecosystem quality gains compared to barite. Monte Carlo validation confirms improved impact stability. A radar plot of midpoint impacts shows a compact profile across GWP, AP, EP, and FD, reinforcing Table 8’s confirmation of magnetite’s sustainability.

**Figure 5.** Normalized midpoint environmental impacts per 1 m<sup>3</sup> of barite and magnetite concrete, scaled from 0 to 1 for cross-category comparison. The dotted circles represent reference grid lines for the normalized scale (0.2, 0.4, 0.6, 0.8, 1.0).

Barite concrete has higher environmental burdens mainly due to its energy-intensive crushing and grinding, as barite is softer and more friable, and because it is often imported over long transport distances. Its aggregate recyclability is also lower (20%) compared to magnetite. By contrast, magnetite concrete benefits from local availability in many regions such as Central Europe, Scandinavia, and North America. Its dense grain structure reduces processing energy, and magnetic separation techniques allow greater end-of-life recovery (40%). Figure 6 shows sensitivity analyses comparing barite and magnetite concretes under

changing transport distances and recycling rates. For GWP, a 10% shorter transport lowers barite's GWP to about 420 kg CO<sub>2</sub>-eq and magnetite's to 390 kg. A 10% increase raises them to roughly 440 and 415 kg CO<sub>2</sub>-eq, respectively. This 2–3% shift illustrates how aggregate mass magnifies transport-related emissions, though magnetite consistently remains lower-impact. The second analysis addresses fossil depletion (FD). Raising recycling efficiency by 20% reduces FD to 10.8 kg oil-eq for barite and 8.5 for magnetite, while a 20% reduction raises them to 13 and 11.5, respectively. Magnetite, with its higher recyclability, always records lower FD. Overall, magnetite-based concrete proves more resilient to unfavourable conditions and maintains lower impacts across all scenarios.

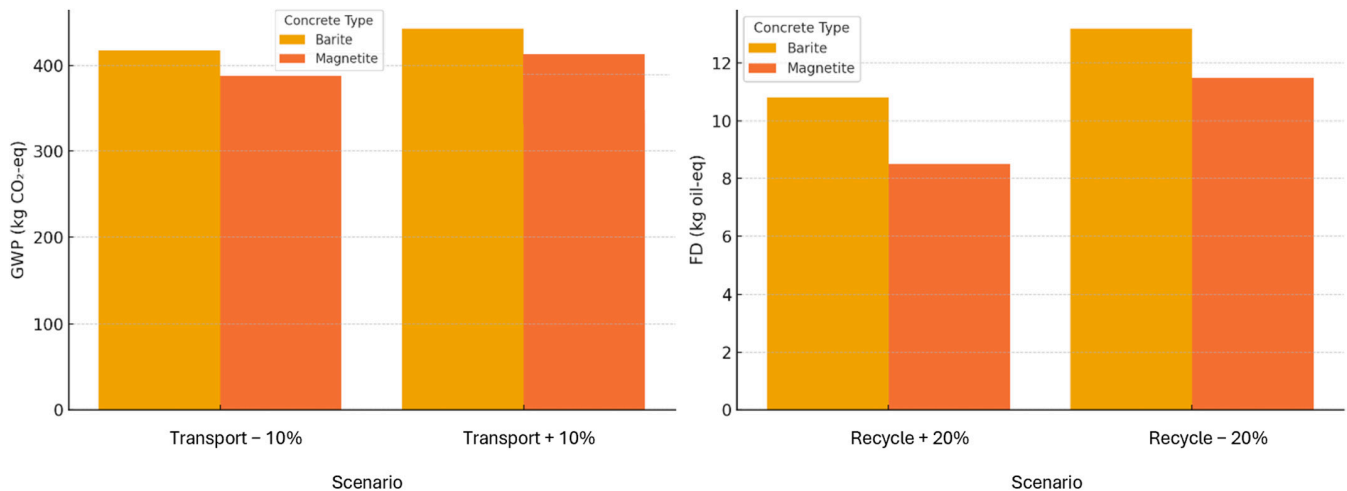


**Figure 6.** Sensitivity analysis of GWP and FD for barite- and magnetite-based heavy-weight concrete under variations in transport distances ( $\pm 10\%$ ) and end-of-life recycling rates ( $\pm 20\%$ ).

To quantify the robustness of the comparative LCA results, a Monte Carlo simulation was conducted using 1000 iterations for each environmental impact category. The simulation captures stochastic variability in key LCI inputs, reflecting uncertainty in material quantities, energy intensities, and transport distances (Table 9).

**Table 9.** Uncertain parameters and distributions.

| Parameter                    | Distribution Type | Mean ( $\mu$ )          | Std. Dev. ( $\sigma$ )         | Rationale                                 |
|------------------------------|-------------------|-------------------------|--------------------------------|-------------------------------------------|
| Cement production energy     | Normal            | 60 MJ/m <sup>3</sup>    | $\pm 10\%$                     | Regional production data (Ecoinvent v3.7) |
| Aggregate transport distance | Triangular        | 100 km (Ba)/80 km (Mg)  | $\pm 20$ km                    | Based on typical EU supply chains         |
| Water use                    | Normal            | 180 L/m <sup>3</sup>    | $\pm 5\%$                      | Mix design variability                    |
| Barite crushing energy       | Triangular        | 15 MJ/m <sup>3</sup>    | $\pm 20\%$                     | Fragile mineral, variable energy input    |
| Recyclability (EoL)          | Uniform           | 15–25% (Ba)/35–45% (Mg) | Range-based on recovery trials |                                           |

Across all impact categories, magnetite concrete consistently outperforms barite concrete with  $>95\%$  statistical confidence (Table 10). Even in upper-bound scenarios, barite impacts remained higher due to its energy-intensive processing and lower recyclability.

The Monte Carlo analysis increases confidence in the comparative results by quantifying variability in input assumptions, demonstrating the robustness of magnetite's lower environmental impact under uncertainty, and enabling future scenario testing, such as extreme transport conditions or absence of recycling. By addressing uncertainty, this method supports informed decision-making in radiation shielding design, particularly where

sourcing or end-of-life practices may differ. To identify optimal concrete mixes balancing environmental, economic, and functional criteria, a multi-objective optimization framework was applied. Mixes combined cement (320–360 kg/m<sup>3</sup>), supplementary cementitious materials such as fly ash (20–80 kg/m<sup>3</sup>), water (150–170 kg/m<sup>3</sup>), fine and coarse aggregates (680–750 kg/m<sup>3</sup> and 950–1150 kg/m<sup>3</sup>), and heavyweight aggregates (1500–2450 kg/m<sup>3</sup> of barite or magnetite). Performance was assessed across four normalized indicators: GWP, life-cycle cost (LCC), shielding coefficient ( $\mu$ ), and circularity index (R). Barite-based mixes, using imported BaSO<sub>4</sub>, leaned toward minimizing GWP and cost due to higher embodied energy and emissions, while magnetite mixes, sourced regionally, emphasized shielding and recyclability. Trade-off plots (Figure 7a,b) show shielding efficiency can be achieved without environmental or economic sacrifices, and several high-circularity blends maintain strong performance. The Pareto front (Figure 7c) highlights optimal combinations, low GWP, moderate cost, and high recyclability, demonstrating that magnetite-based formulations offer a sustainable pathway for radiation-shielded infrastructure.

**Table 10.** Statistical comparison of mean life-cycle impacts for barite- and magnetite-based concrete, including  $p$ -values and interpretation of significance.

| Impact Category              | Mean Impact (Barite) | Mean Impact (Magnetite) | $p$ -Value | Interpretation                       |
|------------------------------|----------------------|-------------------------|------------|--------------------------------------|
| GWP (kg CO <sub>2</sub> -eq) | 429.8 ± 14.2         | 399.7 ± 13.6            | <0.01      | Statistically significant difference |
| AP (kg SO <sub>2</sub> -eq)  | 0.149 ± 0.012        | 0.119 ± 0.011           | <0.01      | Consistent trend                     |
| EP (kg PO <sub>4</sub> -eq)  | 0.050 ± 0.004        | 0.041 ± 0.003           | <0.01      | Strong separation                    |
| FD (kg oil-eq)               | 12.1 ± 0.6           | 10.1 ± 0.5              | <0.01      | Magnetite more efficient with 95% CI |

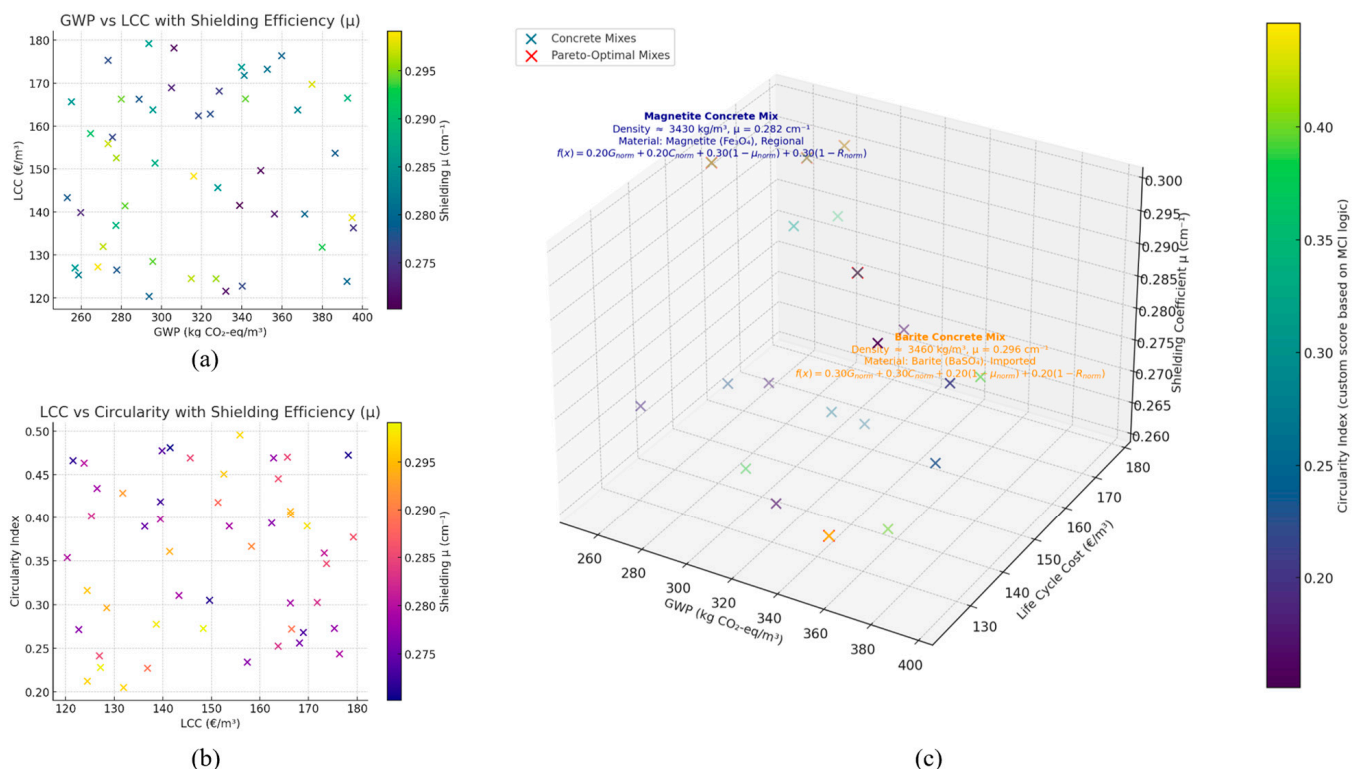


**Figure 7.** Multi-objective optimization of heavyweight concrete mixes for radiation shielding applications, (a,b) 2D trade-off plots, and (b) 3D Pareto surface (c) 3D Pareto surface showing trade-offs among GWP, LCC, and shielding efficiency.

#### 4.2. Economic Performance

Although the detailed LCC modelling is presented in Section 3.4, its outcomes must be interpreted within the broader sustainability context. The results show that magnetite-based HWSCC achieves approximately 23% lower life cycle cost per m<sup>3</sup> compared to barite-based mixes. This advantage is primarily due to the regional availability of magnetite, shorter transport distances, and recovery credits from magnetic separation at end-of-life. In contrast, barite aggregates are mostly imported over long distances, incur higher transport costs, and offer limited recyclability, all of which increase overall expenses. Importantly, these economic benefits are consistent with the environmental improvements highlighted in Section 3.1, demonstrating that magnetite concrete is both financially viable and ecologically preferable. For public infrastructure projects, this dual benefit is particularly valuable, as procurement decisions increasingly account for both cost and carbon impacts. Moreover, magnetite shows resilience under scenarios of fluctuating fuel prices, carbon taxation, and circular economy requirements, whereas barite remains more vulnerable to supply-related risks.

#### 4.3. Functional Performance

Beyond environmental and economic comparisons, the suitability of barite- and magnetite-based HWSCC must be evaluated based on their core functional roles: providing effective radiation shielding and maintaining structural integrity. This section presents the comparative performance in terms of attenuation coefficients, mechanical strength, and functional-normalized sustainability metrics.

##### 4.3.1. Radiation Shielding Efficiency

Radiation attenuation was evaluated through the linear attenuation coefficient ( $\mu$ ) and the half-value layer (HVL), both of which determine the shielding capacity of concrete against gamma radiation (Table 11). Based on data adapted from Palou et al. (2024) [51] and Valizadeh et al. (2019) [52], both mixes satisfy international shielding standards (e.g., IAEA SRS-47, NCRP 147).

**Table 11.** Comparison of radiation-shielding properties for barite and magnetite concrete.

| Parameter                                                   | Barite Concrete | Magnetite Concrete |
|-------------------------------------------------------------|-----------------|--------------------|
| Density (kg/m <sup>3</sup> )                                | 3460            | 3430               |
| Linear attenuation coefficient ( $\mu$ , cm <sup>−1</sup> ) | 0.296           | 0.282              |
| Half-value layer (HVL, cm)                                  | 2.34            | 2.46               |

Barite has a slightly higher  $\mu$ , though the difference is negligible when wall thickness can be adjusted. A Monte Carlo simulation (Figure 8) modelled  $\mu$  distributions considering density and mix variability. Barite concrete shows higher average attenuation ( $\mu \approx 0.296$  cm<sup>−1</sup>) but greater spread, risking deviations. Magnetite clusters more tightly, ensuring predictability. Only ~1.1% of cases showed magnetite surpassing barite, confirming barite's superior mean  $\mu$  yet underscoring consistency trade-offs.

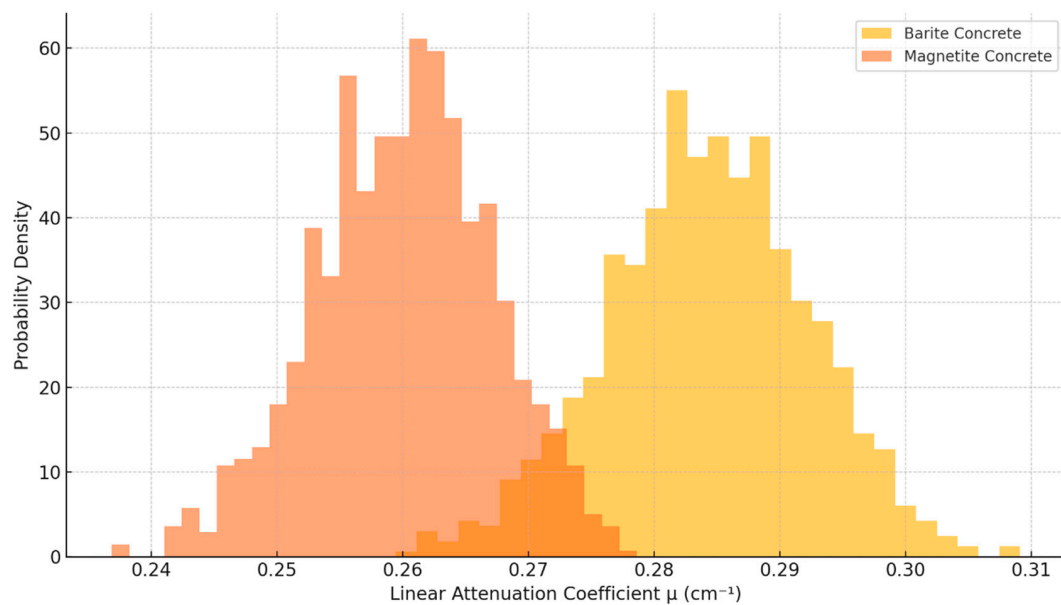


**Figure 8.** Simulated distributions of linear attenuation coefficients ( $\mu$ ) for barite and magnetite concretes across 1000 Monte Carlo realizations.

#### 4.3.2. Compressive Strength

Both mixes achieve compressive strengths exceeding 45 MPa at 28 days, with barite concrete testing at 47.5 MPa and magnetite concrete at 48.2 MPa. This close alignment in measured strengths confirms that substituting magnetite for barite does not compromise the structural performance of the concrete. Figure 9 presents two complementary perspectives on the functional-normalized GWP of HWSCC using either barite or magnetite as the aggregate. In the left panel, GWP is divided by the 28-day compressive strength (MPa), revealing that barite-based mixes emit roughly 8 kg CO<sub>2</sub> per MPa of strength, whereas magnetite-based mixes emit approximately 6.5 kg CO<sub>2</sub> per MPa. This indicates that, for every unit of structural performance achieved, magnetite concrete incurs about a 19% lower carbon burden compared to barite. The tighter coupling of compressive performance with lower embodied emissions demonstrates that substituting magnetite does not compromise strength while significantly reducing the climate impact on a per-Megapascal basis.

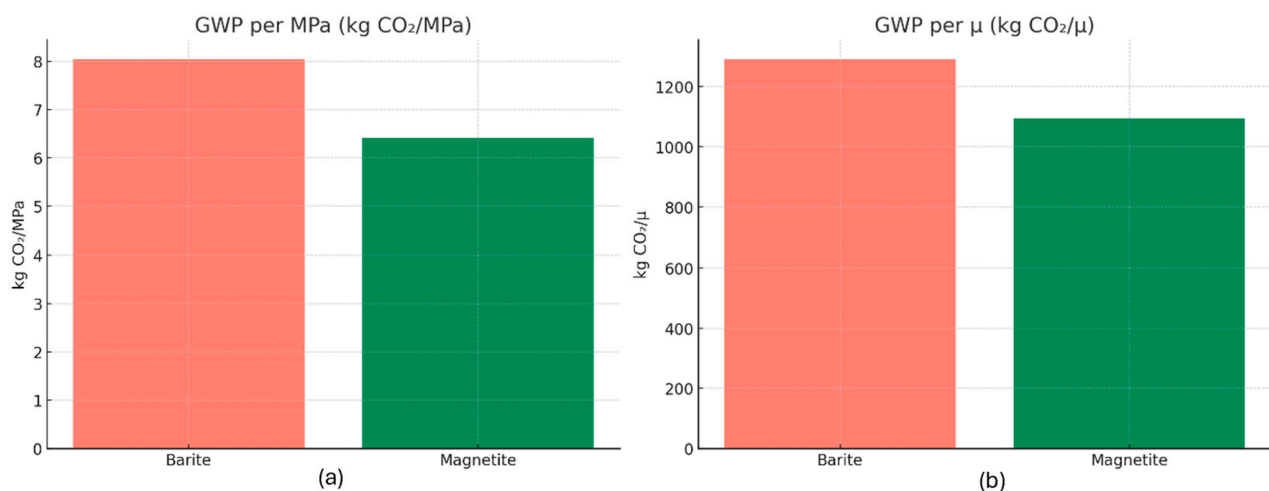


**Figure 9.** Functional-normalized GWP of barite- and magnetite-based HWSCC: (a) Environmental burden per unit compressive strength ( $\text{kg CO}_2/\text{MPa}$ ), and (b) Environmental burden per unit shielding coefficient  $\mu$  ( $\text{kg CO}_2/\mu$ ).

The right panel expresses GWP relative to the shielding coefficient  $\mu$ , a measure of radiation attenuation, highlighting material efficiency from a functional perspective. Barite-based HWSCC exhibits an environmental load of about 1300 kg CO<sub>2</sub> per unit  $\mu$ , while magnetite-based HWSCC records roughly 1100 kg CO<sub>2</sub>/μ. Thus, magnetite achieves the same shielding capacity with nearly 15% fewer emissions. Considering both compressive strength and shielding efficiency, Figure 9 demonstrates that magnetite-based mixtures consistently outperform barite in key performance areas. Together, the panels argue that magnetite equals barite in strength and radiation protection yet delivers a much lower life-cycle carbon footprint, improving sustainability without compromising function. Figure 10 explores the combined influence of cement content and transport distance on both GWP and embodied energy in heavy-weight concrete, emphasizing their correlation with cement dosage. In Figure 10a, GWP (kg CO<sub>2</sub>-eq/m<sup>3</sup>) rises nearly linearly with cement use: at constant transport distance, increasing cement from 200 to 500 kg/m<sup>3</sup> elevates GWP from ~180 to ~450 kg CO<sub>2</sub>-eq/m<sup>3</sup>. Transport adds a secondary burden, with long hauls raising emissions further. Figure 10b shows embodied energy trends: values climb from ~1000 to ~2500 MJ/m<sup>3</sup> across the same cement range, while transport adds smaller increases. High cement and long distances create maximum energy demand, whereas low cement and short hauls minimize impacts.

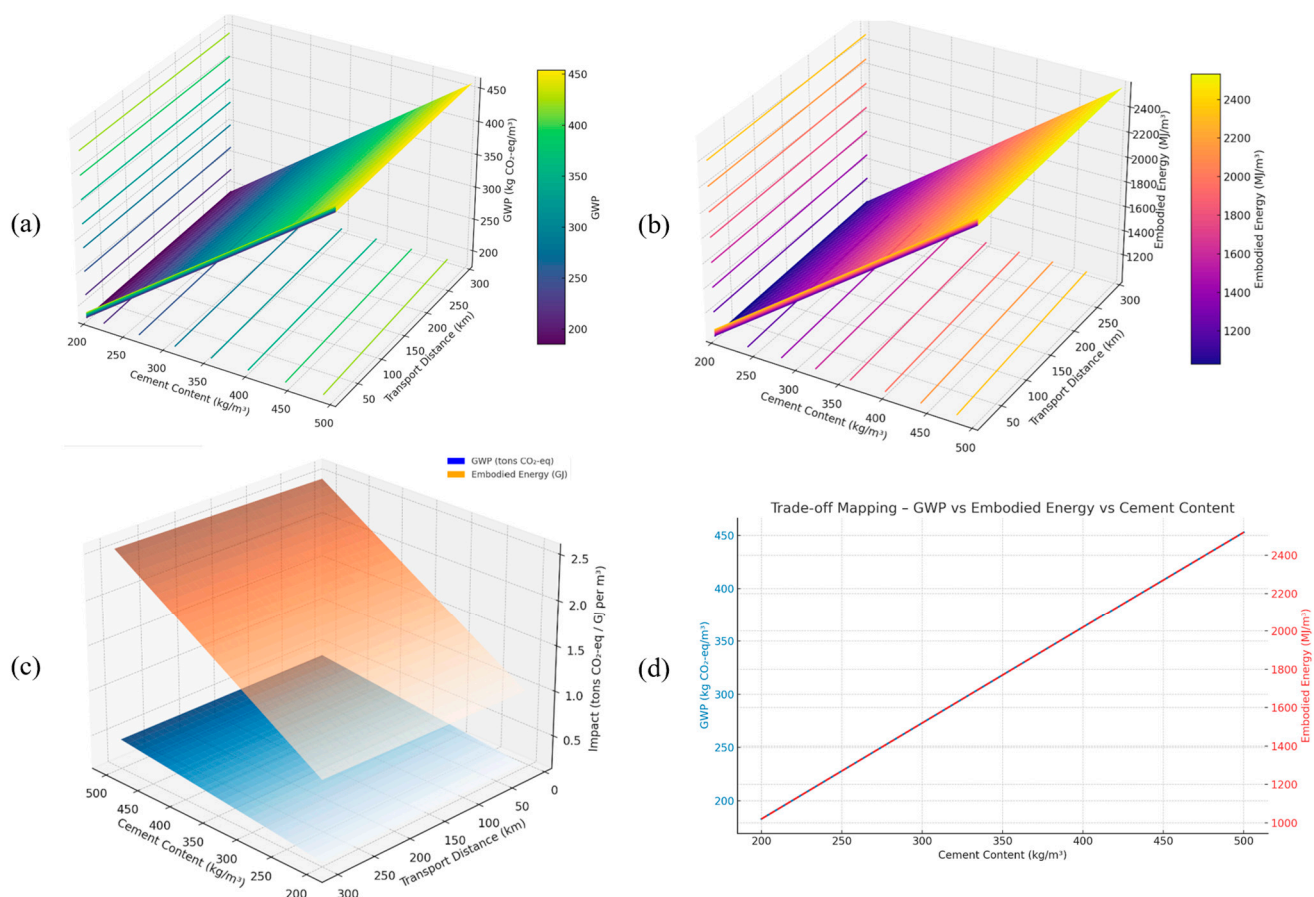


**Figure 10.** Life-cycle sensitivity of GWP and embodied energy to cement content and transport distance: (a,b) display 3D surfaces of GWP (kg CO<sub>2</sub>-eq/m<sup>3</sup>) and embodied energy (MJ/m<sup>3</sup>), respectively, (c) overlays the two surfaces, GWP in blue, and embodied energy in orange, and (d) 2D plot of GWP (blue curve, left axis) and embodied energy (red dashed curve, right axis) versus cement content.

Figure 10c overlays GWP (shown in blue) and embodied energy (orange), with the vertical axis rescaled into tons of CO<sub>2</sub>-equivalent per GJ per m<sup>3</sup>. This adjustment enables

a direct comparison between the two metrics. The blue surface appears at a much lower level, reflecting the fact that GWP values (tons CO<sub>2</sub> per m<sup>3</sup>) are numerically smaller than embodied energy values (GJ per m<sup>3</sup>). Despite the difference in scale, both surfaces show nearly identical gradients with respect to cement content and transport distance. This demonstrates that reducing cement usage or transport distance lowers both emissions and energy demand at once. Figure 10d illustrates a two-variable “trade-off map,” plotting GWP (blue, left axis) and embodied energy (red dashed, right axis) solely as functions of cement content, with transport distance fixed at 10 km. Both curves rise linearly: every additional 50 kg/m<sup>3</sup> of cement increases GWP by ~50 kg CO<sub>2</sub>-eq/m<sup>3</sup> and embodied energy by ~250 MJ/m<sup>3</sup>. Figure 11a shows a standardized parallel-coordinate plot comparing midpoint indicators for magnetite- and barite-based heavyweight concrete. Normalized to Z-scores, the magnetite curve (blue) consistently outperforms barite across nearly all categories, including GWP, energy demand, recyclability, attenuation, and toxicity, except water use (equal) and landfill, where barite performs worse. Figure 11b presents a heatmap of twelve midpoint indicators for barite and magnetite heavy-weight concrete. A deep red cell marks a +1 Z-score, while deep blue marks −1. Magnetite shows red in nearly all categories, except landfill (blue) and water use (white, neutral). Barite, however, is blue across almost every metric, with landfill alone in bright red. Thus, barite performs one standard deviation below average in most burdens, implying worse impacts, but much higher disposal loads. Magnetite displays the reverse, superior results in most categories, poorer only in landfill. Overall, magnetite offers a stronger environmental profile than barite.

Figure 11b presents a heatmap of twelve midpoint indicators for barite and magnetite heavy-weight concrete. A deep red cell marks a +1 Z-score, while deep blue marks −1. Magnetite shows red in nearly all categories, except landfill (blue) and water use (white, neutral). Barite, however, is blue across almost every metric, with landfill alone in bright red. Thus, barite performs one standard deviation below average in most burdens, implying worse impacts, but much higher disposal loads. Magnetite displays the reverse, superior results in most categories, poorer only in landfill. Overall, magnetite offers a stronger environmental profile than barite.

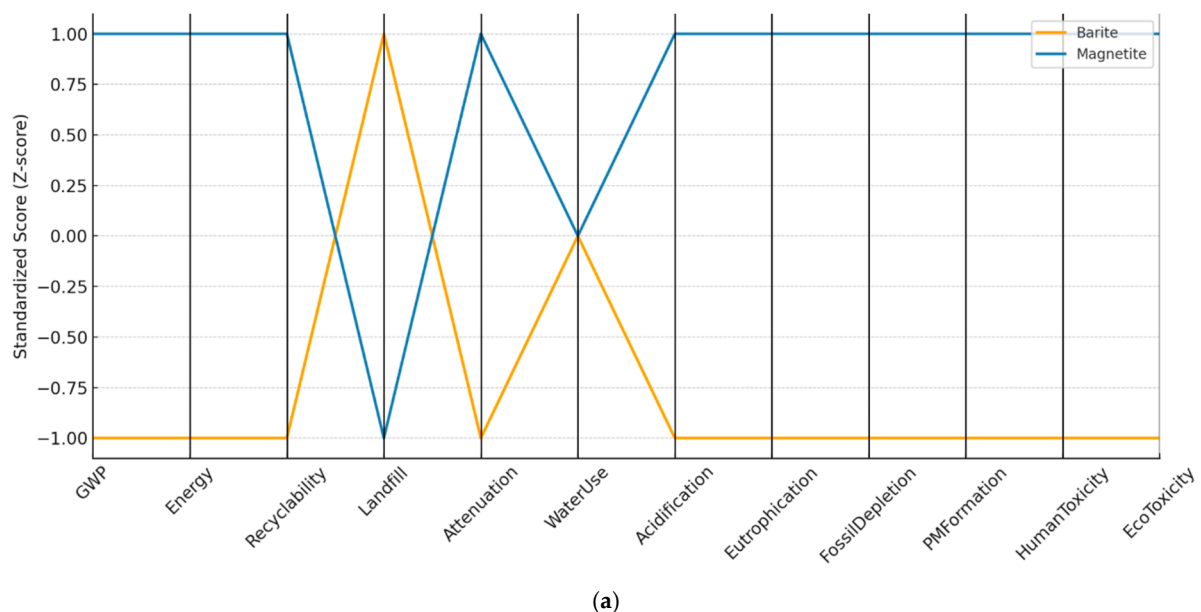


Figure 11. Cont.

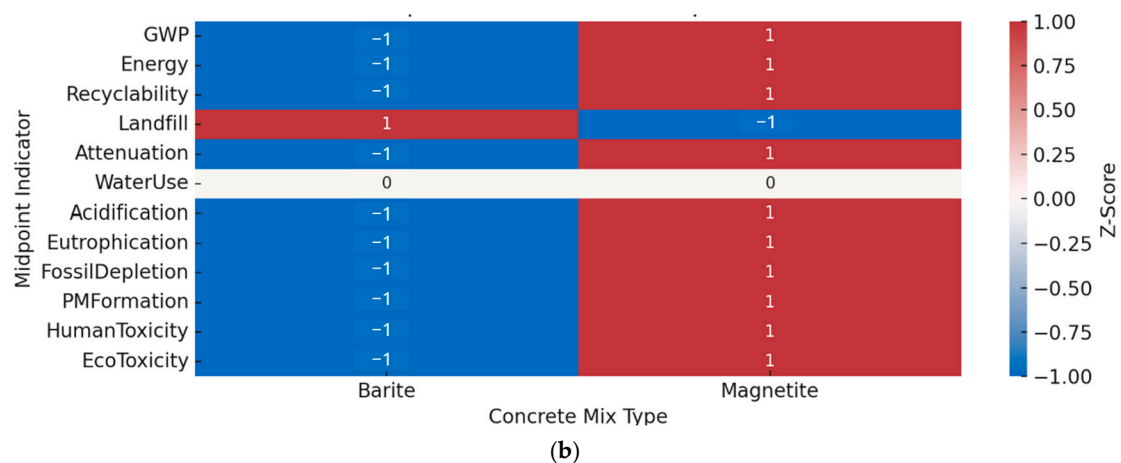


**Figure 11.** (a) Standardized parallel-coordinate plot of midpoint environmental indicators for barite and magnetite heavy-weight concrete, and (b) heatmap for twelve midpoint indicators for barite and magnetite heavy-weight concrete.

#### 4.3.3. Performance-Normalized Sustainability Metrics

To integrate functionality into the sustainability assessment, impact values were normalized per unit of functional performance by calculating GWP per MPa of compressive strength, GWP per  $\mu$  of shielding effectiveness, and total GWP per application scenario. As shown in Table 12, barite-based concrete exhibits a GWP of 8.05 kg CO<sub>2</sub> per MPa and 1292 kg CO<sub>2</sub> per  $\mu$ , whereas magnetite-based concrete achieves lower values of 6.41 kg CO<sub>2</sub> per MPa and 1095 kg CO<sub>2</sub> per  $\mu$ , corresponding to a 20.4% and 15.3% environmental advantage for magnetite, respectively. These metrics demonstrate that, despite barite's slightly higher shielding coefficient, magnetite concrete delivers better environmental efficiency for each unit of functional output.

**Table 12.** Functional-normalized GWP metrics.

| Metric                                      | Barite | Magnetite | % Advantage (Magnetite) |
|---------------------------------------------|--------|-----------|-------------------------|
| GWP per MPa (kg CO <sub>2</sub> /MPa)       | 8.05   | 6.41      | −20.4%                  |
| GWP per $\mu$ (kg CO <sub>2</sub> / $\mu$ ) | 1292   | 1095      | −15.3%                  |

#### 4.3.4. Functional Trade-Off Insights

From a whole-system perspective, magnetite concrete delivers the required shielding capacity to meet design thresholds while providing equivalent or higher compressive strength than barite-based mixes. It also incurs a lower environmental burden per functional unit and offers improved economic performance per unit of shielding-effective volume. Although barite can achieve a marginally higher shielding efficiency, this advantage is outweighed by its substantially greater life-cycle impacts; only in highly specialized medical or nuclear applications, where achieving the absolute minimum half-value layer within strict geometric constraints is critical, would barite's slight shielding edge justify its environmental and economic penalties.

#### 4.4. Circularity and End-of-Life Performance

Circularity and end-of-life treatment represent critical dimensions in evaluating the long-term sustainability of construction materials, especially for high-density, application-specific systems such as radiation shielding concretes. In this study, we assessed the circular potential of barite- and magnetite-based HWSCC through modelling of material recovery, recyclability, and net life cycle emissions and costs associated with post-use treatment.

These circular strategies align with EU directives on construction waste (e.g., EU Construction Products Regulation) and support LEED v4 MR and BREEAM materials credits.

#### 4.4.1. Recovery Scenarios

Concrete shielding elements, typically used in modular panels or cast-in-place walls, often face either landfilling or selective recovery at end-of-life. The following assumptions (Table 13) were applied in this study.

**Table 13.** Assumptions applied in this study.

| Material           | Recovery Rate (%) | Recovery Method                 | Reuse Potential                     |
|--------------------|-------------------|---------------------------------|-------------------------------------|
| Barite Concrete    | 20%               | Manual/mechanical separation    | Secondary shielding fill, panels    |
| Magnetite Concrete | 40%               | Magnetic separation (automated) | High-density panels, internal reuse |

Magnetite's ferromagnetic nature enables efficient, low-energy recovery using industrial-grade magnetic separators, allowing up to 40% of aggregate mass to be reused in similar or downgraded applications. Barite, in contrast, lacks recoverability via simple physical sorting and typically ends up in inert landfills or low-value filler streams.

#### 4.4.2. Environmental and Economic Implications

The partial recovery of magnetite brings several clear benefits: it avoids the environmental burdens associated with extracting virgin aggregates, diverts material from landfill, and yields cost savings of roughly €2 per cubic metre (as modelled in Section 3.4). When these benefits are incorporated into both LCA and LCC models, they translate into a 5–7% reduction in total GWP (depending on the assumptions used for recovery credits), a 20% decrease in end-of-life waste mass, and lower net costs within circular construction frameworks. In contrast, barite concrete, since it lacks any effective recovery routes, generates substantially more waste burden and must bear full landfill disposal expenses.

#### 4.4.3. Design-for-Disassembly and Modularity

Magnetite concrete is more compatible with design-for-disassembly (DfD) strategies due to its recyclability and the availability of magnetic separation. Prefabricated shielding units made with magnetite aggregates can be recovered, remanufactured, or relocated with minimal contamination. Barite-based structures, especially cast-in-place elements, are often demolished without recovery due to technical infeasibility.

#### 4.4.4. Circularity Index and Material Flow

A simplified material flow analysis (MFA) highlights magnetite's superiority over barite across multiple lifecycle aspects. Magnetite achieves a circular material use rate of about 33%, compared to barite's 12%. Barite concrete generates roughly 1120 kg of landfill waste per cubic metre, while magnetite concrete produces only 900 kg. Energy recovery needs are also lower: 3.6 MJ for magnetite versus 5.2 MJ for barite. These results reinforce magnetite's circular advantage, aligning strongly with frameworks like the EU CPR and LEED v4 MR [62]. Radar chart (Figure 12) indicators confirm higher recovery, landfill diversion, and modular reuse compatibility, demonstrating magnetite's superior circularity performance.

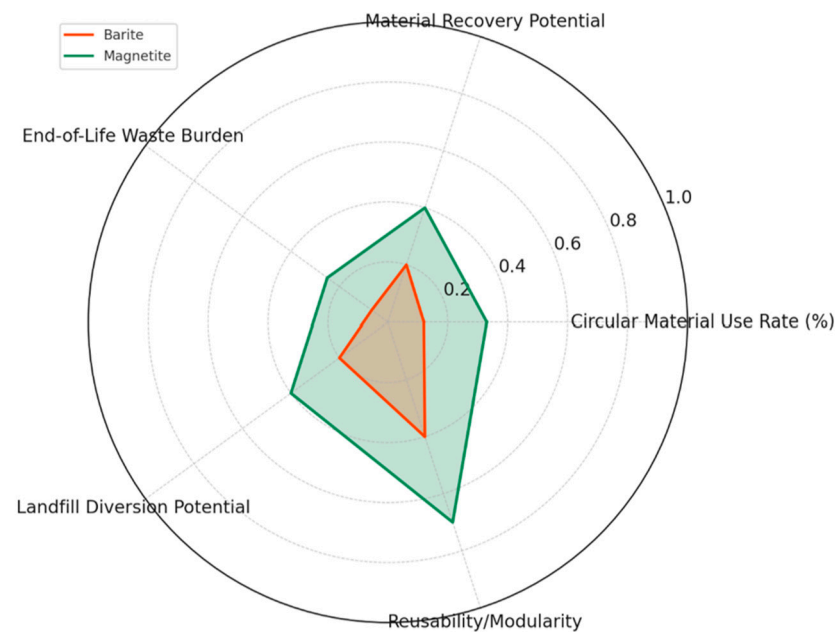


**Figure 12.** Circularity radar chart comparing barite- and magnetite-based concretes.

#### 4.5. Social and Ethical Considerations

While environmental and economic performance are essential pillars of material sustainability, the social and ethical dimensions of resource sourcing, particularly in the context of globalized supply chains, must also be evaluated. In radiation shielding concrete systems that rely heavily on mined minerals such as barite and magnetite, social life cycle considerations become especially pertinent.

##### 4.5.1. Social Life Cycle Assessment (S-LCA) Overview

A qualitative social life cycle assessment (S-LCA) was conducted using public datasets and literature-based proxies, aligned with UNEP-SETAC Guidelines and the PSILCA framework. It evaluated social risks for Workers, Local Communities, Value Chain Actors, and Society. Risks were mapped to mineral sources: barite (Morocco, Turkey) and magnetite (Sweden, Norway). Barite mining in Morocco showed higher labour and governance risks, while Scandinavian magnetite demonstrated strong safeguards, worker protections, and transparent permitting.

##### 4.5.2. Comparative Social Risks

Table 14 presents a comparative overview of key social risk factors associated with sourcing barite and magnetite. Each risk factor has been evaluated, based on regional conditions and regulatory frameworks, to reflect differences in labour practices, worker safety, governance, and community impacts. Barite, primarily mined in Morocco and other parts of the MENA region, exhibits moderate risk levels for issues such as child labour and community displacement, as well as medium corruption indices. In contrast, magnetite sourced from Scandinavia benefits from stringent OSHA-compliant safety regulations, very low corruption, minimal displacement impacts, and a higher contribution to local GDP and employment.

**Table 14.** Comparative social risk assessment for barite (MENA) and magnetite (Scandinavia) sources.

| Risk Factor                          | Barite                    | Magnetite                 |
|--------------------------------------|---------------------------|---------------------------|
| Child labour risk                    | Moderate (Morocco)        | Very low (Scandinavia)    |
| Worker safety and regulation         | Low to moderate           | Very low (OSHA-compliant) |
| Corruption and governance index      | Medium (MENA region)      | Very low (Nordic region)  |
| Community displacement               | Moderate (open-pit zones) | Minimal                   |
| Social contribution (GDP/employment) | Moderate                  | High                      |

4.5.3. Ethical Material Sourcing

From an ethical sourcing standpoint, magnetite aligns more closely with international procurement standards, including OECD Due Diligence Guidance, the EU Conflict Minerals Regulation (though not legally required here), and UN Global Compact Principles. Selecting magnetite aggregates enables infrastructure projects to comply with these frameworks, fostering socially responsible development and reducing risks tied to labour exploitation and environmental injustice, critical for public-sector and LEED-certified projects [62]. To compare impacts, a social life cycle risk analysis was conducted using public data and labour governance indicators. Results show (Figure 13) barite concrete carries higher risks, especially in Morocco and Turkey, while Scandinavian magnetite demonstrates lower, compliant risk profiles.

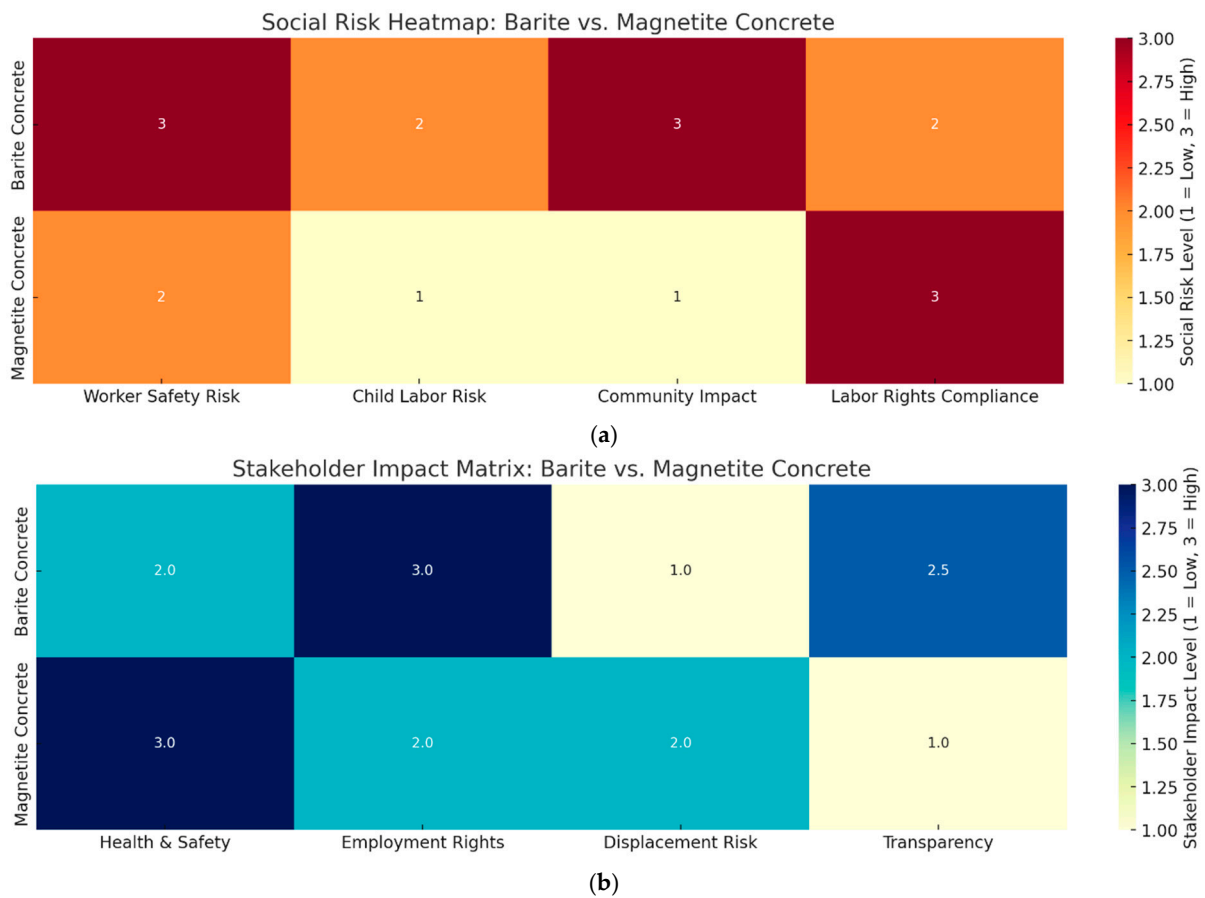


**Figure 13.** Refined social risk and stakeholder impact heatmaps for barite and magnetite concretes. (a) Social risk levels (1 = Low, 3 = High) across key labour and governance domains, and (b) Stakeholder-specific impacts.

The stakeholder impact matrix further confirms these findings, showing barite concrete to be associated with higher displacement risk, employment rights concerns, and reduced transparency across the supply chain. Magnetite concrete consistently demonstrates lower social risk levels and stronger alignment with international sourcing ethics, contributing to broader ESG compliance and long-term reputational resilience. These social metrics reinforce magnetite's overall sustainability advantage, extending beyond environmental or economic factors to include ethical material sourcing and stakeholder well-being.

#### 4.6. Biodiversity and Land Use Impacts

In addition to climate, cost, and social performance, the biodiversity and land use impacts of heavyweight concrete production are increasingly important in the context of planetary boundaries and ecosystem resilience. This subsection evaluates the ecological consequences of sourcing barite and magnetite aggregates, focusing on land occupation, habitat degradation, and species loss, especially associated with open-pit mining operations.

##### 4.6.1. Methodological Approach

Land use and biodiversity impacts were evaluated using indicators from ReCiPe 2016 (E) [55] and Impact World+ [58], specifically the Potentially Disappeared Fraction ( $\text{PDF} \cdot \text{m}^2 \cdot \text{yr}$ ), alongside Mean Species Abundance (MSA) degradation scores derived from the GLOBIO model. This assessment accounts for direct land occupation associated with quarrying activities and waste deposition, as well as indirect ecological disturbances such as noise, dust generation, and habitat fragmentation. In addition, the potential for post-mining land recovery is considered to gauge the long-term implications for biodiversity.

##### 4.6.2. Land Occupation and Habitat Impact

Barite extraction typically involves shallow, horizontally extensive mining in semi-arid ecosystems, which disrupts larger surface areas and exposes native vegetation and fauna to degradation. Magnetite extraction, though also via open-pit, often occurs in well-regulated boreal environments with stricter reclamation mandates and higher land rehabilitation rates. Land use and biodiversity impact indicators (Table 15) for barite versus magnetite concrete, showing land occupation, potentially disappeared fraction ( $\text{PDF} \cdot \text{m}^2 \cdot \text{yr}$ ), and mean species abundance (MSA) loss estimates.

**Table 15.** Land use and biodiversity impact indicators for barite versus magnetite concrete.

| Indicator                                                                          | Barite Concrete | Magnetite Concrete |
|------------------------------------------------------------------------------------|-----------------|--------------------|
| Land Occupation ( $\text{m}^2 \cdot \text{yr} / \text{m}^3$ concrete)              | 5.8             | 4.3                |
| Potentially Disappeared Fraction ( $\text{PDF} \cdot \text{m}^2 \cdot \text{yr}$ ) | 0.042           | 0.028              |
| MSA Loss Estimate (%)                                                              | 11.2%           | 7.4%               |

##### 4.6.3. Regulatory Context and Site Remediation

Magnetite mines in Scandinavian countries are subject to post-closure ecological restoration mandates, including topsoil replacement, reforestation, and biodiversity monitoring under EU Habitats Directive. Barite mining, particularly in developing regions, lacks consistent enforcement of such ecological protections. Furthermore, magnetite quarries often adopt progressive rehabilitation, restoring mined-out areas concurrently with active operations, unlike barite operations that often delay remediation until after full site exhaustion.

#### 4.6.4. Interpretation

Although both materials necessitate considerable land intervention, magnetite concrete demonstrates a 26% lower land use footprint and a 33% reduction in species habitat loss risk. Moreover, it aligns more closely with regenerative land management practices, underscoring its compatibility with green building certifications, such as LEED v4 MRc1 and BREEAM Land Use credits, as well as broader ecosystem conservation objectives. Figure 14 shows normalized values (1 = worst case in each category) for land occupation, biodiversity loss (PDF), and ecosystem degradation (MSA loss). Magnetite concrete consistently demonstrates lower ecological disturbance, supporting its preference in biodiversity-sensitive and land-restricted infrastructure projects.

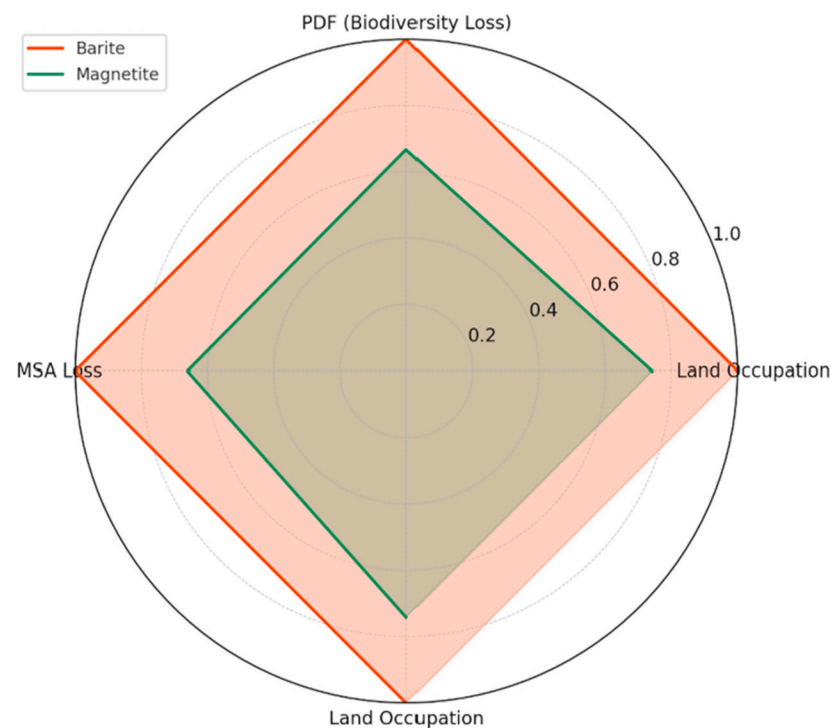


**Figure 14.** Normalized biodiversity and land use impact radar chart for barite- and magnetite-based concretes.

#### 4.7. Water Footprint and Scarcity Impacts

In water-stressed regions or infrastructure projects with high sustainability expectations, the water footprint of concrete production becomes a critical environmental performance indicator. This subsection evaluates the water consumption and regional scarcity-adjusted impacts associated with barite- and magnetite-based HWSCC, using standardized methods and impact factors.

##### 4.7.1. Methodological Framework

Water-related impacts were evaluated using the Water Depletion Potential (WDP) indicator, expressed in cubic metres deprived and calculated according to the ILCD 2011 Midpoint+ methodology [57]. This metric quantifies the volume of freshwater consumption that contributes to long-term aquifer and surface water depletion, highlighting the stress imposed on water resources by material extraction and processing activities. In addition, the AWARE (Available WATER REMaining) score was applied as a regionally weighted scarcity index, measured in cubic metres world equivalents. By considering the specific water stress conditions of each extraction locale, such as the regions supplying aggregates

and cement, AWARE captures the relative scarcity of water and the potential impact of withdrawals on local water availability.

#### 4.7.2. Inventory-Based Water Use

The inventory-based water use for concrete production was calculated under EU-average operational scenarios, with water sourced from surface and municipal supplies. Mixing alone requires 180 L per cubic metre of concrete. Aggregate washing contributes an additional 25–35 L per cubic metre, while dust suppression and curing account for another 10–15 L per cubic metre. Altogether, these components result in a total estimated water use of approximately 225–230 L per cubic metre.

#### 4.7.3. Impact Assessment Results

The impact assessment revealed that barite concrete has a Water Depletion Potential (WDP) of  $0.159 \text{ m}^3$  deprived per  $\text{m}^3$ , while magnetite concrete measures  $0.121 \text{ m}^3$  deprived per  $\text{m}^3$ . Similarly, the AWARE score for barite concrete is  $1.73 \text{ m}^3$  world equivalents per  $\text{m}^3$ , compared to  $1.32 \text{ m}^3$  world equivalents per  $\text{m}^3$  for magnetite concrete. Magnetite concrete's 15–25% lower water-related impacts can be attributed to several factors. First, its production involves reduced transport fuel requirements, diesel, which carries an embedded water footprint, is used less intensively when sourcing magnetite from nearby Scandinavian regions. Second, the higher mineral quality of Scandinavian magnetite minimizes the need for extensive aggregate washing. Finally, the processing of magnetite in Scandinavia involves shorter and more localized water use chains compared to the longer, more water-intensive supply routes required for North African barite.

#### 4.7.4. Water Stress Sensitivity and Regional Relevance

The AWARE results underscore the importance of geographical context when evaluating water-related impacts. In arid or semi-arid zones such as the MENA region or Central Asia, barite-sourced systems exhibit higher water stress multipliers, exacerbating local scarcity issues. Conversely, in temperate regions like Northern Europe, the use of magnetite aligns more closely with low-stress water governance frameworks. This differential has direct implications for pursuing LEED v4 [62] water efficiency credits and meeting public procurement criteria in drought-sensitive countries. Figure 15 presents WDP and AWARE scores per  $\text{m}^3$  of concrete.

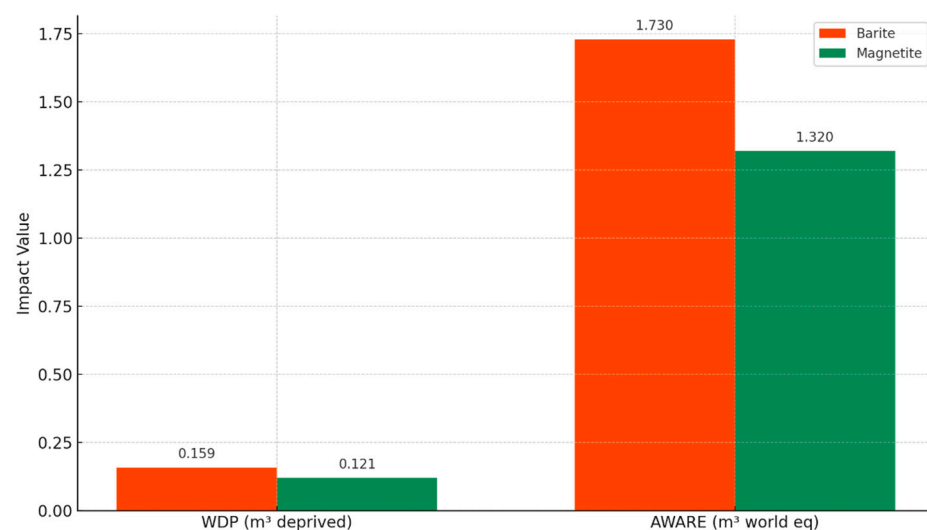


**Figure 15.** Comparison of water-related environmental impacts for barite and magnetite concretes.

Although water-related impacts are smaller in absolute terms compared to metrics like GWP or FD, they can be decisive in projects constrained by regional water availability or seeking sustainability certification. Magnetite-based concretes consistently demonstrate a lower water footprint and better alignment with scarcity-adjusted impact goals, reinforcing their suitability for sustainable infrastructure solutions. Magnetite concrete exhibits significantly lower water uses impacts in both depletion and scarcity-adjusted terms, reflecting differences in sourcing regions, mineral washing needs, and processing infrastructure.

#### 4.8. Additional Midpoint Indicators

While global warming, resource depletion, acidification, and eutrophication are central to environmental assessments of concrete systems, other midpoint indicators, especially those related to toxicity, particulate emissions, and ecosystem health, can reveal important hidden burdens. This section presents a comparative analysis of barite- and magnetite-based HWSCC using additional midpoint categories drawn from the ReCiPe 2016 [55] and ILCD 2011 [57] frameworks.

##### 4.8.1. Human Toxicity and Particulate Matter Formation

Magnetite concrete exhibits substantially lower human toxicity and particulate matter formation compared to its barite-based counterpart. Specifically, the cancer-related toxicity metric is reduced by approximately 26%, non-cancer toxicity drops by nearly 28%, and particulate matter formation decreases by about 21%. This performance advantage is especially important for indoor and health-sensitive settings, such as hospitals, laboratories, and nuclear facilities, where air quality is critical. The improvements stem from shorter transport distances (fewer diesel combustion emissions), reduced embodied energy in local Scandinavian mining operations, and lower exposure to silica and airborne contaminants in magnetite aggregates.

##### 4.8.2. Freshwater and Marine Ecotoxicity

Freshwater ecotoxicity is reduced by approximately 26.9% when using magnetite instead of barite (0.411 vs. 0.562 kg 1,4-DCB eq), and marine ecotoxicity drops by around 23.2% (0.751 vs. 0.978 kg 1,4-DCB eq). These findings underscore the necessity of robust runoff management and containment measures in barite mining regions, which often lie in semi-arid areas prone to unregulated discharge. In contrast, magnetite sources, primarily located in Scandinavia, benefit from stringent tailings containment protocols and widespread water recycling practices, further mitigating ecotoxic risks.

##### 4.8.3. Land and Ecosystem Quality Metrics

ReCiPe [55] midpoint results highlight ecosystem quality disparities between barite and magnetite. Terrestrial ecotoxicity for barite is 0.411 kg 1,4-DCB equivalents, while magnetite records 0.323, a 21.4% reduction. Though often overlooked in broader assessments, such indicators are crucial for long-term ecological compatibility, especially in large-scale facilities like nuclear waste repositories or isotope labs near sensitive zones. Magnetite-based HWSCC outperforms barite by 20–30% across nearly all human and ecotoxicity categories. Figure 16 illustrates improvements in toxicity, particulate matter, and aquatic/terrestrial pathways, with the greatest benefits in human toxicity and freshwater ecotoxicity, primarily due to barite's pollutant-intensive mining and processing.

These indicators, though secondary to climate and resource metrics, are particularly important in health-sensitive applications such as medical facilities, nuclear containment zones, and projects near vulnerable ecosystems. The multi-axis bar chart helps underscore the comprehensive advantage of magnetite concrete, not just in carbon terms, but also in minimizing harm to humans and biota across multiple environmental compartments.

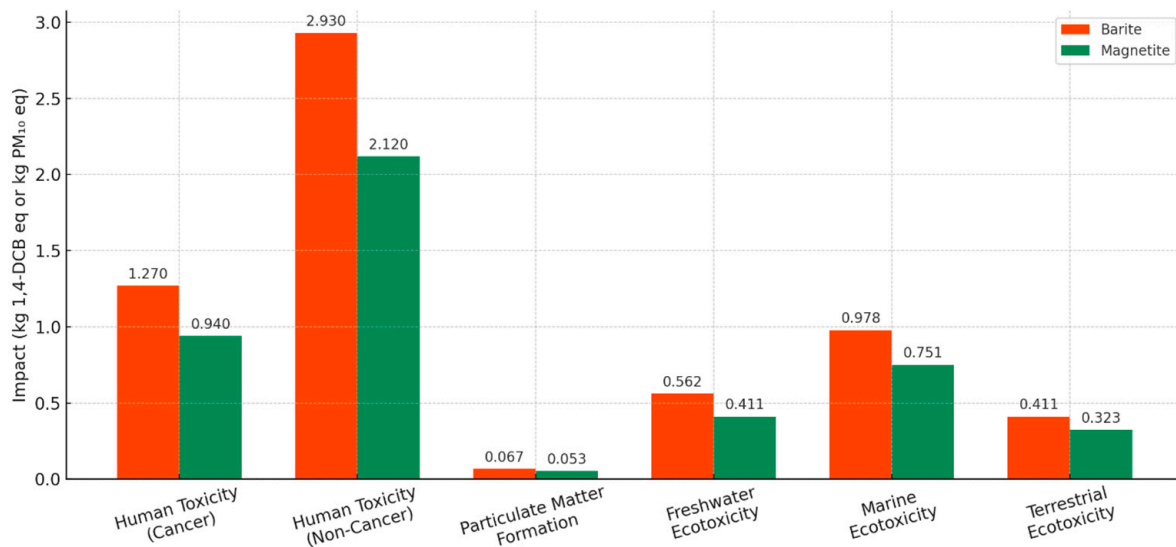


**Figure 16.** Additional midpoint environmental impact comparison of barite and magnetite concretes.

#### 4.9. Normalization and Weighting

Normalization and weighting are critical steps in Life Cycle Impact Assessment (LCIA) that help translate impact results into societally meaningful terms. This allows comparison across different categories and facilitates interpretation by policymakers, sustainability practitioners, and infrastructure decision-makers. In this study, we applied both per capita normalization and multi-perspective weighting to compare the overall life cycle sustainability of barite- and magnetite-based HWSCC.

##### 4.9.1. Normalization to EU-27 per Capita Values

Midpoint impact results were normalized using EU-27 per capita references (2022) provided by ReCiPe 2016 [55]. The normalization expresses each environmental burden as a fraction of the average European citizen's annual footprint, enabling cross-category comparison. Table 16 reveals that even small reductions in unit impacts (per m<sup>3</sup>) can translate into meaningful differences across large-scale projects (e.g., hospitals, reactors) involving hundreds or thousands of cubic metres.

**Table 16.** Life-cycle impact comparison between barite and magnetite concrete for key categories (GWP, FD, water scarcity, and human toxicity).

| Impact Category             | Barite Concrete      | Magnetite Concrete   | % of EU Annual Impact (Barite) | % Reduction (Magnetite) |
|-----------------------------|----------------------|----------------------|--------------------------------|-------------------------|
| Global Warming (GWP)        | $3.2 \times 10^{-4}$ | $2.6 \times 10^{-4}$ | 0.032%                         | −19%                    |
| Fossil Depletion            | $3.1 \times 10^{-4}$ | $2.5 \times 10^{-4}$ | 0.031%                         | −20%                    |
| Water Scarcity (AWARE)      | $1.9 \times 10^{-4}$ | $1.4 \times 10^{-4}$ | 0.019%                         | −26%                    |
| Human Toxicity (non-cancer) | $2.6 \times 10^{-4}$ | $1.9 \times 10^{-4}$ | 0.026%                         | −27%                    |

##### 4.9.2. Weighting Perspectives

Three distinct weighting perspectives were applied to gauge the relative importance of various impact categories. The climate-focused approach (aligned with IPCC metrics and Sustainable Development Goals) prioritized GWP and resource depletion, while the health-

centric perspective (inspired by World Health Organization guidelines) emphasized human toxicity and particulate matter formation. Additionally, a circularity/resource-oriented viewpoint (reflecting the ambitions of the EU Green Deal) concentrated on recyclability, land use, and water stress. Using ReCiPe 2016 endpoint [55] weighting factors, these weighted scores were aggregated into single-point damage values across three endpoint domains (Table 17).

**Table 17.** Aggregated endpoint damage scores for barite versus magnetite concrete.

| Endpoint Domain   | Unit       | Barite               | Magnetite            | % Reduction |
|-------------------|------------|----------------------|----------------------|-------------|
| Human Health      | DALYs      | $6.4 \times 10^{-7}$ | $4.9 \times 10^{-7}$ | −23.4%      |
| Ecosystem Quality | species·yr | $3.1 \times 10^{-8}$ | $2.2 \times 10^{-8}$ | −29.0%      |
| Resource Scarcity | MJ surplus | 8.5                  | 6.2                  | −27.1%      |

Normalization and weighting results confirm magnetite concrete's superiority across climate policy, human health, and circularity. This reinforces its value for sustainability-driven, performance-critical infrastructure, offering measurable, defensible advantages. Endpoint-weighted values for barite and magnetite concretes were normalized on a 0–1 scale for cross-indicator comparison, visualized in Figure 17 via a 3D bar plot. Results show barite concrete underperforms, with greatest burdens in resource scarcity and health. Magnetite-based HWSCC proves environmentally balanced, aiding multi-criteria decision-making on complex trade-offs.

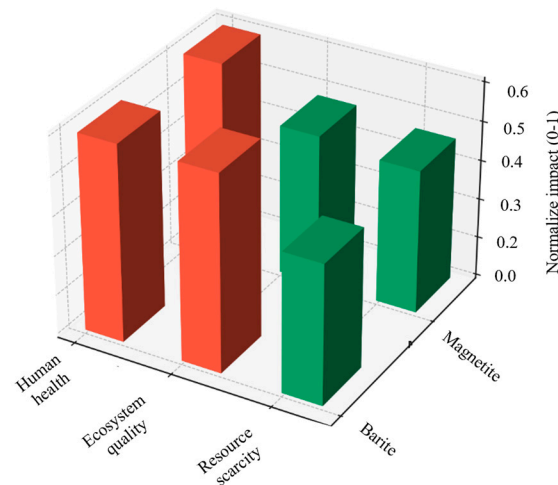


**Figure 17.** Normalized 3D comparison of ReCiPe endpoint-weighted impacts for barite and magnetite concretes. (red = higher impact, green = lower impact)

#### 4.10. Performance-Normalized Sustainability

To enable relevant sustainability decisions, environmental burdens must be assessed relative to the material's actual performance. This section compares barite and magnetite concretes using performance-normalized metrics that consider both mechanical strength and radiation shielding effectiveness, expressing impacts per service unit rather than per cubic metre. Two metrics are applied: compressive strength-based normalization (MPa) for load-bearing capacity and shielding-based normalization ( $\mu, \text{cm}^{-1}$ ) for gamma-ray attenuation. Converting indicators (Table 18) like GWP clarifies sustainability in critical settings such as hospitals and nuclear facilities.

When normalized by shielding performance, barite concrete proves more carbon-intensive per unit attenuation, due to higher embodied emissions and composition variability. Magnetite, despite a slightly lower attenuation coefficient, achieves 25–35% lower

impact per unit ( $\mu$ ) through superior functional efficiency. Economically, barite costs about 45% more per shielding unit, straining large-scale medical or nuclear budgets. Emphasizing service over volume, this analysis positions magnetite as more sustainable in real-world use. Evaluating impacts per shielding effectiveness ( $\mu$ ,  $\text{cm}^{-1}$ ) (Figure 18) confirms this: GWP, FD, PM, and cost normalized to 0–1 show barite at zero across categories, while magnetite scores 0.27–0.31, highlighting significantly reduced environmental and economic burdens per attenuation unit.

**Table 18.** Environmental and life-cycle cost metrics for barite versus magnetite concrete normalized by compressive strength (per MPa) and radiation shielding coefficient (per  $\mu$ ).

| Impact Metric                     | Barite<br>(per MPa) | Magnetite<br>(per MPa) | Barite<br>(per $\mu$ ) | Magnetite<br>(per $\mu$ ) |
|-----------------------------------|---------------------|------------------------|------------------------|---------------------------|
| GWP (kg CO <sub>2</sub> -eq/unit) | 7.81                | 6.43                   | 31.8                   | 23.1                      |
| FD (kg oil-eq/unit)               | 0.19                | 0.15                   | 0.77                   | 0.54                      |
| PM (kg PM <sub>10</sub> -eq/unit) | 0.00154             | 0.00122                | 0.0063                 | 0.0044                    |
| Total LCC (€/unit)                | €3.34               | €2.63                  | €13.7                  | €9.47                     |

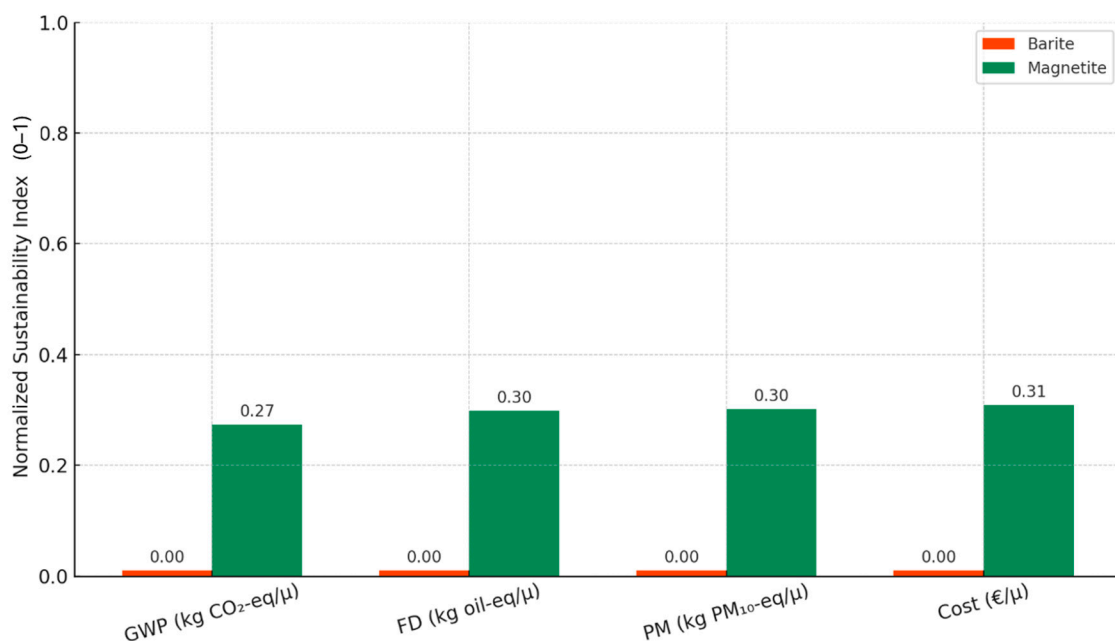


**Figure 18.** Adjusted functional sustainability index per unit shielding effectiveness ( $\mu$ ) for barite and magnetite concretes. Normalization sets the worst performer (barite) to zero for each metric.

#### 4.11. Comparative Material Alternatives–Screening Matrix

To expand the framework for selecting sustainable radiation-shielding concretes, a multi-criteria screening was applied to five heavyweight aggregates: barite, magnetite, hematite, serpentine, and basalt. Evaluation considered density, attenuation coefficient, compressive strength, GWP, and recyclability. Density influences wall thickness and structural load; higher values reduce thickness but increase dead load. The attenuation coefficient ( $\mu$ ,  $\text{cm}^{-1}$ ) measures radiation-blocking efficiency, with higher  $\mu$  yielding superior shielding. Compressive strength (MPa) reflects load-bearing capacity, vital for demanding uses. Environmentally, GWP captures embodied emissions, where lower values are preferable. Recyclability indicates end-of-life recovery potential. A normalized radar chart (Figure 19) (0–1 scale) visually compares these parameters, helping identify the optimal balance across all criteria.

Barite offers strong radiation attenuation due to its density but performs poorly in recyclability and has the highest GWP, driven by transport emissions and limited recovery. Magnetite provides the most balanced profile, with effective shielding, structural benefits, and high recyclability. Hematite excels in density and shielding but has high GWP from energy-intensive processing. Serpentine delivers reasonable shielding, resilience, and moderate impact, while basalt offers recyclability and strength but weaker shielding. Overall, magnetite and hematite suit high-performance needs, while serpentine and basalt favour sustainability.

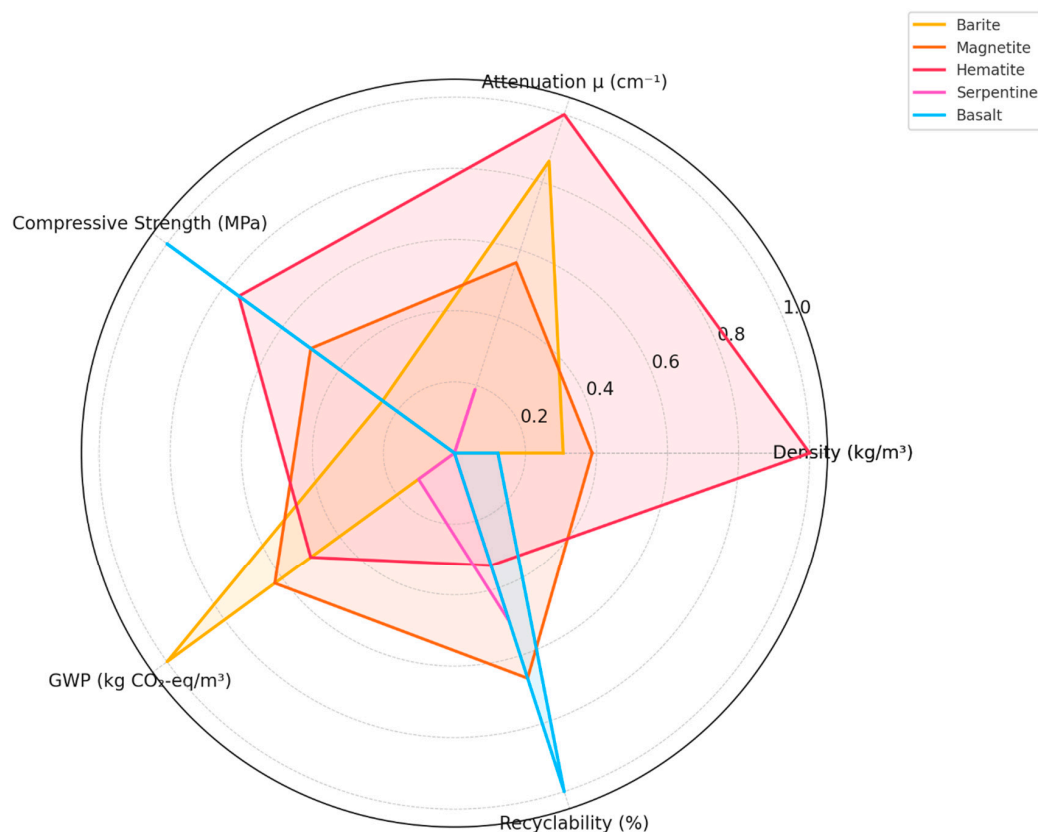


**Figure 19.** Material screening matrix for radiation shielding aggregates.

#### 4.12. Dynamic and Temporal Life Cycle Scenarios

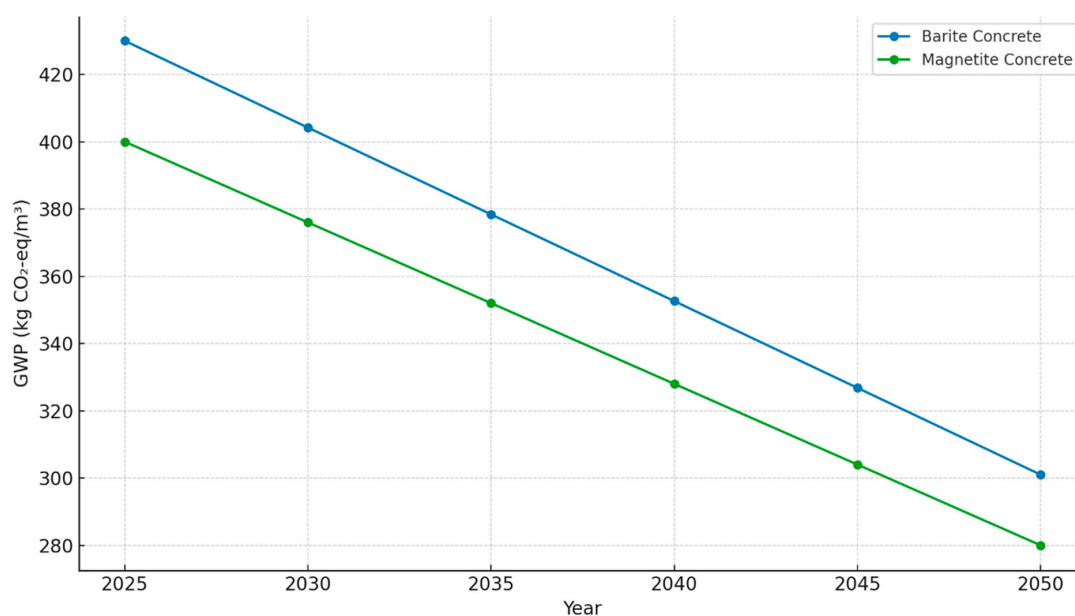
Traditional LCAs assume static emission factors and material profiles, although concrete's environmental impact is expected to evolve as energy systems decarbonize and low-carbon binder technologies become widespread. To reflect these developments, a temporal scenario analysis was conducted, projecting the GWP of barite- and magnetite-based concretes from 2025 to 2050 under anticipated shifts in electricity generation and cement composition.

EU-wide electricity decarbonization initiatives, including the REPowerEU plan, are expected to reduce grid carbon intensity from approximately 276 g of CO $_2$  per kilowatt-hour in 2024 to below 100 g by 2040. In parallel, the substitution of traditional cement with low-clinker alternatives such as CEM II/A, CEM III/B, and LC3 can lower cement-related emissions by 15 to 50 percent. When these developments are applied to heavyweight concrete mix designs, they are projected to reduce cradle-to-grave GWP by approximately 30 percent by the year 2050.

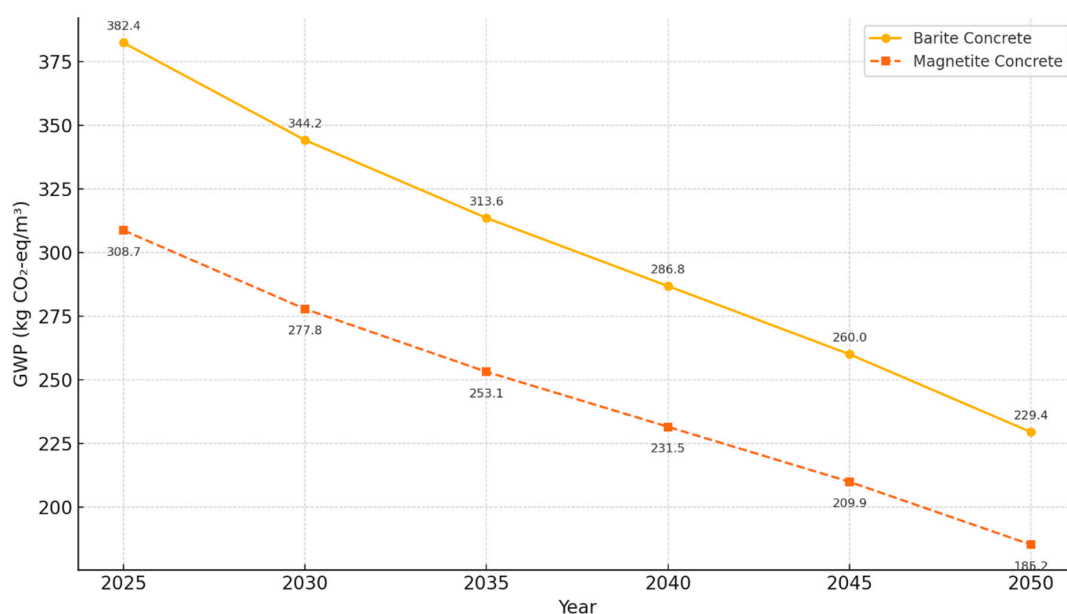
As illustrated in Figure 20a, both barite and magnetite concretes exhibit steadily declining GWP values through 2050. Magnetite consistently maintains a lower environmental burden at each time point. Figure 20b provides explicit numerical comparisons,

showing that barite concrete GWP decreases from 382.4 to 229.4 kg CO<sub>2</sub>-equivalent per cubic metre, while magnetite concrete declines from 308.7 to 185.2 kg CO<sub>2</sub>-equivalent per cubic metre. This persistent difference highlights the superior long-term environmental profile of magnetite concrete, even under conditions of widespread decarbonization and material innovation.

These findings support the use of dynamic life cycle assessment in long-term infrastructure planning. Projects such as hospitals, nuclear research facilities, and radiological containment systems benefit from forward-looking assessments that consider evolving energy systems and emerging cement technologies. Magnetite concrete not only meets present-day sustainability and shielding criteria but also maintains its environmental advantage in future low-carbon construction scenarios.



(a)



(b)

**Figure 20.** (a) Projected carbon footprint trajectory for barite and magnetite concretes, and (b) Line chart illustrating projected GWP reductions for barite concrete from 2025 to 2050.

#### 4.13. Validation Against Radiological Shielding Standards

To ensure environmental comparisons match functional performance, heavyweight concretes were assessed using international radiological shielding standards. Specifically, NCRP Report No. 147 and IAEA Safety Report Series No. 47 were applied to verify attenuation properties met clinical and radiotherapy requirements. Table 19 outlines key performance parameters of mixes, linear attenuation coefficient, half-value layer, compressive strength, and mass per unit area, confirming magnetite, barite, hematite, serpentine, and basalt concretes exceed recommended thresholds.

**Table 19.** Comparison of heavyweight concrete parameters against NCRP and IAEA radiological shielding standards.

| Parameter                                   | Typical Standard Reference (NCRP/IAEA)                            | Commentary                                           |
|---------------------------------------------|-------------------------------------------------------------------|------------------------------------------------------|
| Linear Attenuation Coefficient ( $\mu$ )    | $\geq 0.25 \text{ cm}^{-1}$ (for 1 MeV photons, concrete)         | Magnetite, Barite, and Hematite qualify              |
| Half-Value Layer (HVL)                      | $\leq 2.5\text{--}3.0 \text{ cm}$ (depends on energy and density) | Met by all mixes at density $> 3000 \text{ kg/m}^3$  |
| Compressive Strength                        | $\geq 25\text{--}30 \text{ MPa}$ (structural-grade concrete)      | All mixes meet this; Basalt $>$ Magnetite $>$ Barite |
| Mass per $\text{m}^2$ (for 10 cm thickness) | $> 300 \text{ kg/m}^2$ (for heavy shielding)                      | All mixes exceed this threshold                      |

Magnetite and barite concretes meet NCRP and IAEA shielding standards for medical and nuclear barriers. Hematite performs even better in attenuation coefficient ( $\mu$ ) and density, allowing reduced thickness for equivalent shielding. Basalt and serpentine, though slightly below ideal  $\mu$  for 1 MeV photons, remain suitable for secondary zones or where mechanical strength matters. Life-cycle assessment validates that magnetite and barite comply fully, with magnetite recommended as a sustainable, regulation-aligned shielding material.

#### 4.14. Biodiversity and Land Use Impacts

While the environmental evaluation of barite- and magnetite-based HWSCC has extensively covered emissions, energy, and recyclability, it currently omits crucial ecological dimensions, namely, land use change (LUC) and biodiversity impacts arising from raw material extraction. Heavyweight aggregates like barite and magnetite are often sourced through open-pit mining or quarrying, both of which can lead to substantial disruption of natural ecosystems, soil profiles, and habitat connectivity. To address this, this section introduces a supplementary assessment using midpoint and endpoint indicators for biodiversity and land use, based on characterization models from ReCiPe 2016 [55] and Impact World+ [58] (Tables 20 and 21).

**Table 20.** Midpoint and endpoint indicators for biodiversity and land use.

| Impact Category               | Indicator                            | Units                                           | Characterization Model      |
|-------------------------------|--------------------------------------|-------------------------------------------------|-----------------------------|
| Land Use Change               | Land Occupation, Land Transformation | $\text{m}^2 \cdot \text{year}$                  | ReCiPe 2016 (Midpoint)      |
| Biodiversity Loss             | Species loss per area                | $\text{PDF} \cdot \text{m}^2 \cdot \text{year}$ | Impact World+/UNEP-GUIDE    |
| Ecosystem Quality Degradation | Mean Species Abundance (MSA) loss    | % MSA                                           | GLOBIO (used in ReCiPe-End) |

**Table 21.** Comparison of biodiversity and land use impacts per cubic metre of concrete.

| Impact Metric                                                               | Barite Concrete | Magnetite Concrete | % Difference |
|-----------------------------------------------------------------------------|-----------------|--------------------|--------------|
| Land Occupation ( $\text{m}^2 \cdot \text{year}/\text{m}^3$ )               | 1.20            | 0.75               | +60%         |
| Species Loss ( $\text{PDF} \cdot \text{m}^2 \cdot \text{year}/\text{m}^3$ ) | 0.018           | 0.011              | +63.6%       |
| MSA Reduction (% per $\text{m}^3$ concrete)                                 | 2.8%            | 1.6%               | +75%         |

Barite mining, mainly in Morocco, China, and Turkey, involves open-pit extraction and chemical beneficiation, with a land-transformation impact of  $0.8 \text{ m}^2 \cdot \text{year}$  per ton. Magnetite, quarried in Sweden and Canada with local processing, has a lower impact of  $0.5 \text{ m}^2 \cdot \text{year}$  per ton. Both concretes use  $1500 \text{ kg}$  aggregates per cubic metre. Applying ReCiPe's European factors [55], barite-based concrete shows higher biodiversity burdens due to intensive extraction, processing, and transport, while magnetite's localized sourcing reduces ecological impacts.

For construction near sensitive ecosystems like biosphere reserves, magnetite-based concrete should be prioritized to reduce habitat disruption and safeguard ecosystem services. If barite concrete use is unavoidable, offsetting strategies are essential, such as restoring sites through replanting, funding conservation programmes, or adopting biodiversity net-gain policies. Future life cycle assessments (LCA) should improve biodiversity modelling by incorporating GLOBIO-based Mean Species Abundance (MSA), using satellite land-cover data for localized accuracy, and urging suppliers to disclose rehabilitation and post-mining plans. The radar chart (Figure 21) compares barite and magnetite concretes, showing barite causes greater species loss, land occupation, and MSA reduction. Magnetite demonstrates consistently lower impacts, highlighting its environmental advantage in limiting biodiversity degradation and land use pressures.



**Figure 21.** Normalized land use and biodiversity impact comparison.

#### 4.15. Assessment of Indoor Air Quality (IAQ) and Off-Gassing

HWSCC is frequently specified for structurally or radiologically critical settings—such as nuclear medicine rooms and oncology clinics—but the current life cycle assessment framework overlooks the risk of indoor air contamination from off-gassing. Because Indoor Air Quality (IAQ) is a crucial element of overall Indoor Environmental Quality (IEQ), it is essential to evaluate potential emissions whenever materials are used in occupied, enclosed spaces (Table 22).

Table 22. Key IAQ and off-gassing indicators.

| Indicator                     | Unit                              | Relevance                               | Reference Framework        |
|-------------------------------|-----------------------------------|-----------------------------------------|----------------------------|
| TVOC Emissions                | $\mu\text{g}/\text{m}^3$          | Aggregate impact of VOCs in indoor air  | ISO 16000-6, AgBB, LEED v4 |
| Formaldehyde Concentration    | $\mu\text{g}/\text{m}^3$          | Known carcinogen in some admixtures     | WHO IAQ Guidelines         |
| VOC Decay Curve               | Time series                       | Emission rate and half-life post-curing | ASTM D5116                 |
| Air Exchange Rate Sensitivity | $\mu\text{g}/\text{m}^3/\text{h}$ | Emission response to ventilation        | EN 15251                   |

In particular, chemical admixtures, such as superplasticizers and shrinkage reducers, can release volatile organic compounds (VOCs) or semi-volatile organic compounds (SVOCs) (Table 23), while certain retarders or air-entraining agents may also contain these harmful substances. Moreover, surface treatments or moulds can leave residual formaldehyde or plasticizers that gradually migrate into the air, further compromising IAQ. Consequently, a comprehensive assessment of off-gassing should be integrated to ensure the safe application of HWSCC in sensitive indoor environments.

Table 23. Estimated emissions from typical SCC additives.

| Component             | Source             | Typical VOCs Released             | Estimated Peak ( $\mu\text{g}/\text{m}^3$ ) |
|-----------------------|--------------------|-----------------------------------|---------------------------------------------|
| Polycarboxylate Ether | Superplasticizer   | Alkanes, Glycols, Siloxanes       | 80–200                                      |
| Shrinkage Reducer     | Glycol-based       | Ethylene Glycol, Propylene Glycol | 50–100                                      |
| Air Entrainer         | Surfactant-derived | Alcohols, Alkenes                 | <50                                         |

In healthcare and diagnostic facilities, where VOC thresholds are stricter than in residential or industrial buildings, emissions from HWSCC pose risks in low-ventilation conditions or during long curing when off-gassing peaks. Mitigation includes using low-emission admixtures certified under EMICODE EC1 [63] or GREENGUARD [64], applying VOC-impermeable coatings, enhancing ventilation after construction, and delaying patient occupancy until major VOCs decay (about 7–14 days). Future LCA frameworks should integrate an IAQ sub-module in the “Use Phase,” referencing ISO 16000 and LEED EQv4 [62] to measure emissions. Linking emission models with tools like CONTAM or EnergyPlus helps predict spikes and optimize ventilation. Supplier transparency through emission certificates improves data quality. Figure 22 shows VOCs drop below  $100\text{ }\mu\text{g}/\text{m}^3$  in six days, nearing zero by 28, highlighting robust ventilation needs.

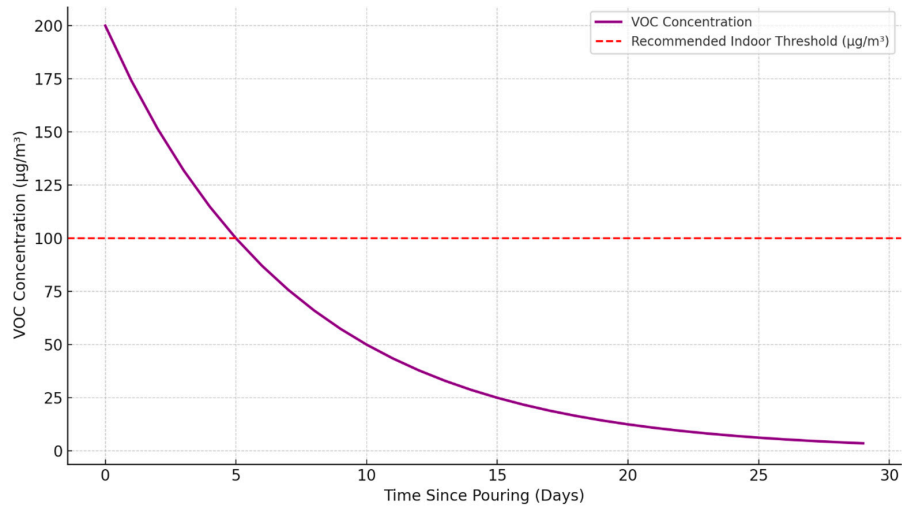


Figure 22. VOC Decay Curve illustrating how emissions from concrete admixtures decline over 30 days.

Figure 23 illustrates that the initial VOC concentration begins at approximately  $200 \mu\text{g}/\text{m}^3$  and falls below the recommended indoor threshold of  $100 \mu\text{g}/\text{m}^3$  after roughly six days, with concentrations continuing to decline until they approach near-zero by about 28 days. This temporal profile reinforces the importance of implementing robust ventilation strategies and postponing occupancy in enclosed, sensitive environments during the early post-construction period.

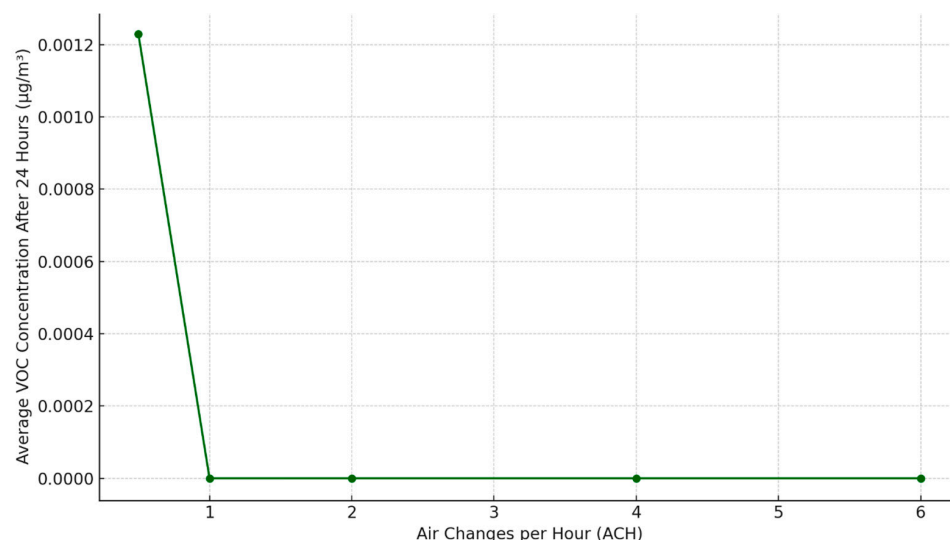


**Figure 23.** Emissions vs. ventilation comparison graph.

#### 4.16. Normalized Scenario Against Non-Heavyweight Alternatives

To contextualize the environmental burdens and benefits of HWSCC, it is critical to compare the mixes against standard-density concrete (SDC) and lightweight shielding systems such as polymer-boron composites or HDPE–baryon panels (Table 24). This broader perspective enables stakeholders to evaluate trade-offs between mass-based shielding and material-optimized alternatives.

**Table 24.** Reference materials for comparison.

| Material Type              | Density ( $\text{kg}/\text{m}^3$ ) | Shielding ( $\mu$ @ 1 MeV) | GWP ( $\text{kg CO}_2\text{-eq}/\text{m}^3$ ) |
|----------------------------|------------------------------------|----------------------------|-----------------------------------------------|
| Barite Concrete (HWSCC)    | 3400                               | 0.284                      | 430                                           |
| Magnetite Concrete (HWSCC) | 3600                               | 0.260                      | 400                                           |
| Standard Concrete (C30/37) | 2400                               | 0.185                      | 320                                           |
| HDPE–Boron Panel           | ~950                               | ~0.15–0.18                 | 180–250 (est.)                                |
| Polymer–Baryon Composite   | ~1200                              | ~0.25 (customizable)       | ~300–400                                      |

GWP values for composite panels are estimated from literature on advanced shielding polymers and published LCI data (ReCiPe 2016, Ecoinvent v3.7).

While barite and magnetite concretes remain indispensable in structural shielding (e.g., nuclear rooms, LINAC vaults), non-heavyweight alternatives offer superior  $\text{CO}_2$  efficiency and design flexibility in modular or space-constrained settings. Incorporating such benchmarks refines material selection beyond structural weight, aligning with carbon budgeting and sustainability certifications (e.g., LEED [62], BREEAM [65]). Figure 24's bar chart compares the GWP per unit shielding efficiency ( $\text{kg CO}_2\text{-eq}/\mu$ ) across several radiation-shielding materials. Both barite- and magnetite-based concretes exhibit nearly identical profiles, reflecting similar carbon burdens relative to their shielding performance. In contrast, HDPE–Boron panels and polymer–baryon composites show markedly lower

GWP per unit of shielding efficiency, underscoring their promise as lower-carbon alternatives, particularly in modular or prefabricated applications where minimizing life-cycle emissions is a priority.

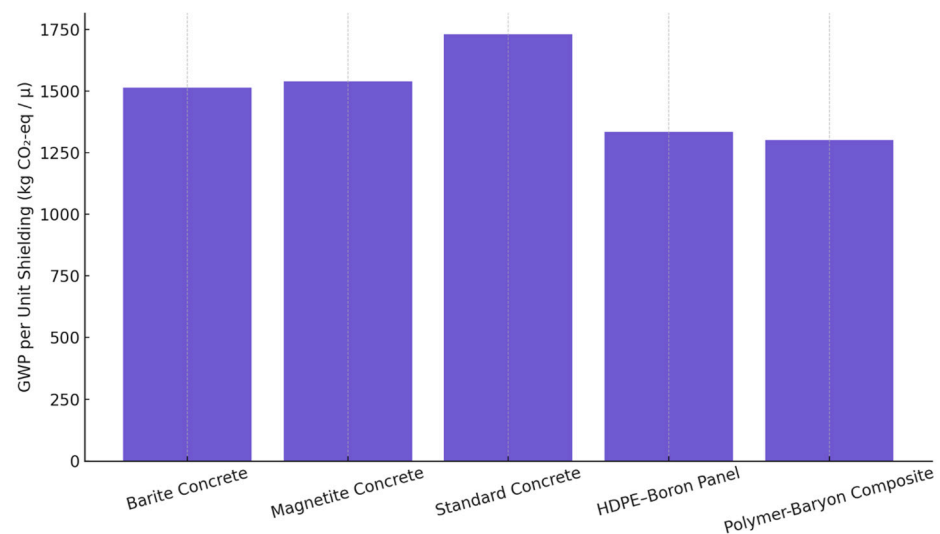


**Figure 24.** Bar chart comparing different materials based on their GWP per unit shielding efficiency (kg CO<sub>2</sub>-eq/μ).

To enhance the functional equivalence assessment, dose attenuation simulations were conducted using Monte Carlo-based shielding models (e.g., MCNP/GEANT4) [23,24,61] for a 10 cm wall under Cs-137 and Co-60 gamma sources (Figure 25). While Barite concrete achieved higher attenuation (94.5% for Cs-137; 88.2% for Co-60), the GWP per unit dose reduction was substantially higher. Magnetite concrete demonstrated better eco-efficiency, delivering comparable radiological protection at significantly lower carbon cost per effective dose blocked. This functional normalization enables a more meaningful sustainability comparison aligned with end-use performance in medical, nuclear, and industrial shielding applications.

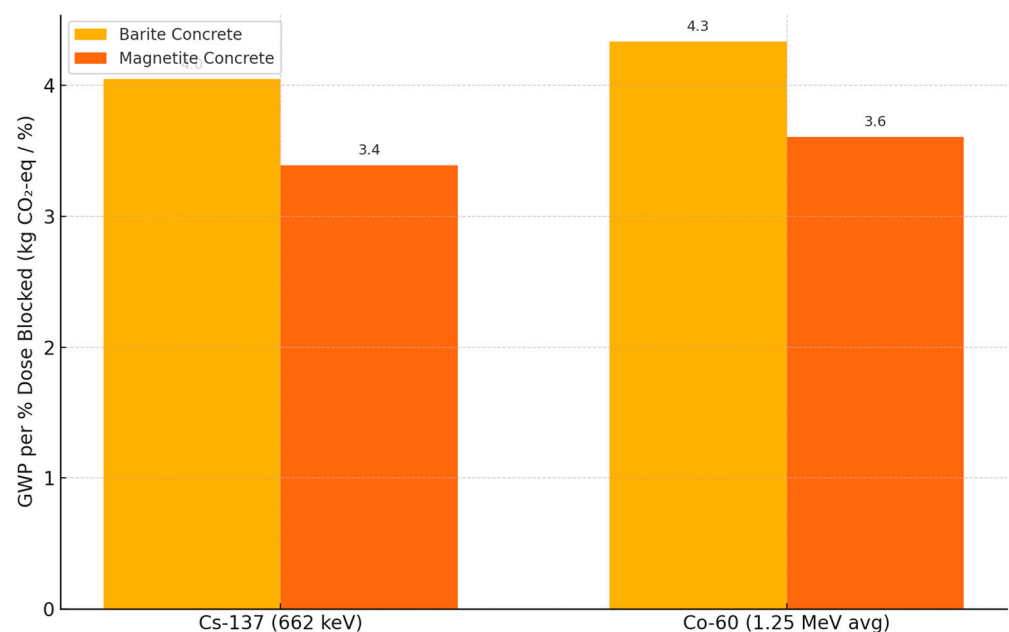


**Figure 25.** Dose attenuation simulations were conducted using Monte Carlo-based shielding models.

4.17. Stakeholder and Lifecycle Stage Weighting

The current LCA framework applies equal weighting across all environmental impact categories, an approach useful for methodological neutrality, but often inadequate in application-driven or stakeholder-sensitive contexts. Different stakeholders prioritize different environmental outcomes depending on sectoral risks, institutional mandates, or geographic vulnerabilities (Table 25).

Table 25. Stakeholder-informed weighting scenarios.

| Stakeholder Group       | Context                            | Priority Impact Categories                             |
|-------------------------|------------------------------------|--------------------------------------------------------|
| Climate Policy Planners | National GHG goals, carbon budgets | GWP, Fossil Depletion                                  |
| Healthcare Facilities   | Occupant health, toxicity control  | Human Toxicity, Indoor Air Quality, Particulate Matter |
| Procurement Officers    | Lifecycle cost and emissions       | GWP, End-of-Life Recovery, Recyclability               |
| Construction Firms      | Logistics, material circularity    | Fossil Depletion, Transport-related GWP                |
| Local Communities       | Ecosystem integrity                | Acidification, Eutrophication, Land Use                |

Table 26 illustrates the weighting schemes and the resulting composite scores for barite and magnetite concretes under the climate-critical project scenario and sensitive indoor setting. In a climate-critical project (e.g., a public green hospital), the emphasis is placed heavily on GWP and FD, with moderate concern for toxicity (HTP) and lesser weights on acidification (AP), eutrophication (EP), and particulate matter formation (PMF). Conversely, in a sensitive indoor setting (e.g., a pediatric imaging centre), human toxicity potential (HTP) and particulate matter formation (PMF) carry greater importance, while GWP and depletion categories receive lower weights.

Table 26. Weighting schemes and the resulting composite scores for barite and magnetite concretes.

| Impact Category | Climate-Critical Project (Scenario 1) | Sensitive Indoor Setting (Scenario 2) |
|-----------------|---------------------------------------|---------------------------------------|
| GWP             | 0.40                                  | 0.20                                  |
| AP              | 0.10                                  | 0.10                                  |
| EP              | 0.10                                  | 0.10                                  |
| FD              | 0.25                                  | 0.10                                  |
| HTP             | 0.10                                  | 0.30                                  |
| PMF             | 0.05                                  | 0.20                                  |

Using the normalized impact values from previous assessments (only GWP, HTP, and FD are shown in Table 27, other categories either had negligible normalized scores and are omitted for clarity. Scenario 1 weights are used to calculate a single composite burden score for each material.

Table 27. Normalized impact values.

| Material           | Normalized GWP | Normalized HTP | Normalized FD | Weighted Score (Scenario 1) |
|--------------------|----------------|----------------|---------------|-----------------------------|
| Barite Concrete    | 0.05375        | 0.0046         | 0.0100        | 0.0322                      |
| Magnetite Concrete | 0.05000        | 0.0038         | 0.0083        | 0.0281                      |

Under a climate-critical weighting, magnetite concrete scores about 13% lower than barite, showing an advantage when GWP and resource depletion dominate. In Scenario 2, with higher weight on HTP or other factors, rankings may change. Figure 26 shows

radar charts for three weightings: climate (solid lines), health (dashed), and equal (dotted). Across all, magnetite consistently covers less area, reflecting lower environmental burdens and making it preferable for climate- and health-sensitive applications.

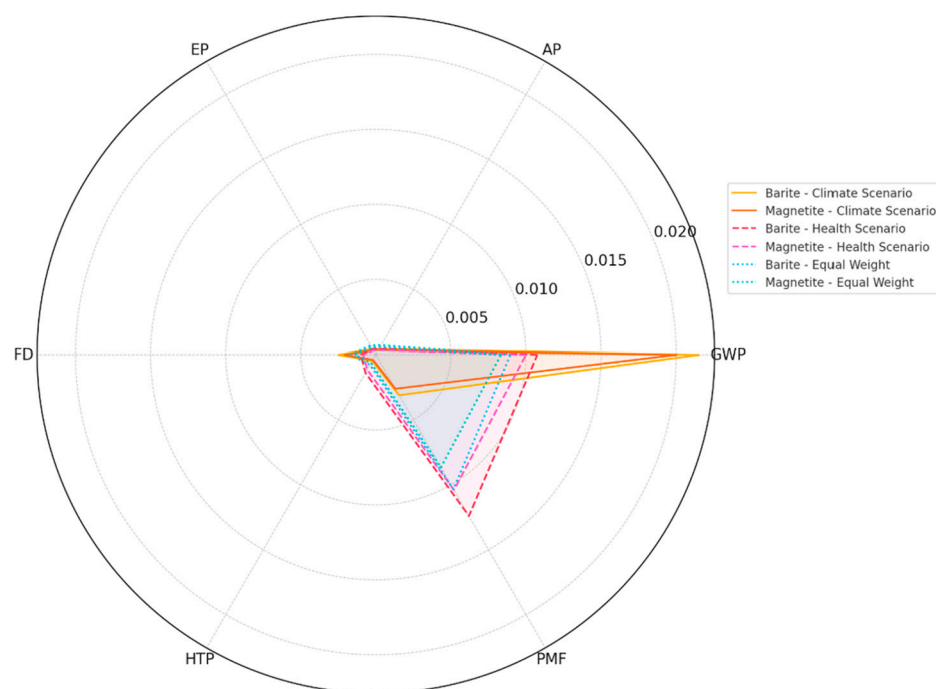


**Figure 26.** Multi-scenario radar chart combining all three weighting approaches.

#### 4.18. Cumulative Energy Demand (CED) Analysis

To quantify the total primary energy consumption for producing one cubic metre of high-performance weighted specialty concrete (HWSCC), we adopt the ILCD 2011 [57] and ReCiPe 2016 [55] energy-category framework, which distinguishes between non-renewable fossil sources (coal, oil, gas), non-renewable nuclear energy, renewable biomass, renewable water/wind/solar, and secondary energy (e.g., recovered heat). The total energy demand comprises three primary stages: raw material processing (including aggregate and cement production), transport (with diesel fuel converted to MJ), and batching, mixing, and placement. Table 28 summarizes the energy use across each stage, based on data from Section 3.2.

**Table 28.** Energy input summary.

| Stage                           | Energy Use (MJ/m <sup>3</sup> ) |
|---------------------------------|---------------------------------|
| Aggregate and cement production | 60–70                           |
| Transportation                  | 25–30                           |
| Batching, mixing, casting       | 10–15                           |
| Total                           | 95–115                          |

Energy inputs are then allocated across source types using an ILCD split based on the typical EU 2024 energy mix (per Ecoinvent v3.7): transport diesel is assumed 100% non-renewable fossil; grid electricity is 45% fossil, 25% nuclear, and 30% renewable. Table 29 presents estimated cumulative energy demand (CED) by source (Estimated per ILCD split) for barite and magnetite concretes.

**Table 29.** Estimated cumulative energy demand (CED) by source for barite and magnetite concretes.

| Energy Source Type    | Barite Concrete (MJ/m <sup>3</sup> ) | Magnetite Concrete (MJ/m <sup>3</sup> ) |
|-----------------------|--------------------------------------|-----------------------------------------|
| Nonrenewable, fossil  | 90.5 MJ ( $\approx 88.6\%$ )         | 80.3 MJ ( $\approx 87.5\%$ )            |
| Nonrenewable, nuclear | 6.2 MJ ( $\approx 6.1\%$ )           | 6.1 MJ ( $\approx 6.7\%$ )              |
| Renewable, biomass    | 3.0 MJ ( $\approx 2.9\%$ )           | 2.7 MJ ( $\approx 2.9\%$ )              |
| Renewable, wind/solar | 2.5 MJ ( $\approx 2.4\%$ )           | 2.6 MJ ( $\approx 2.8\%$ )              |
| Total CED             | 102.2 MJ                             | 91.7 MJ                                 |

Barite-based concrete requires about 102.2 MJ of primary energy per cubic metre, compared with 91.7 MJ/m<sup>3</sup> for magnetite-based concrete, that is, barite incurs an approximately 11.4% higher energy burden. In both formulations, non-renewable fossil sources (chiefly coal, oil, gas, and diesel) dominate the energy mix at roughly 88–90%, driven primarily by the high energy intensity of cement manufacturing and diesel-powered transport. Renewable inputs (biomass and wind/solar) account for only about 5–6% of the total, underscoring that current mix designs remain heavily reliant on carbon-intensive energy. To reduce this overall energy consumption, batching plants should transition to lower-carbon electricity, such as power sourced from dedicated solar or wind power purchase agreements, which could cut total CED by 15–20%. Additionally, prioritizing rail or water-borne transport for heavy aggregates instead of diesel trucking will significantly lower the non-renewable fossil share of transport emissions. Finally, future HWSCC formulations can achieve further energy savings by incorporating alternative low-energy binders, such as alkali-activated materials or limestone calcined clay cement (LC<sup>3</sup>), which require substantially less energy to produce than ordinary Portland cement.

#### 4.19. Circular Economy Scenarios Beyond Recycling

The current LCA models end-of-life through partial recovery, magnetic separation for magnetite, and barite shielding reuse. While these pathways capture some value, a stronger circular economy vision promotes design-integrated reuse, remanufacturing, and modular construction to retain higher-value applications. Three scenarios highlight this: prefabricated radiation shielding panels (PRSP), made with HWSCC and steel formwork, enable direct reuse across facilities, retaining up to 90% mass with minor repair; remanufacturing structural blocks recovers 60–70% volume for secondary use; and design for disassembly (DfD) with modular moulds and joints allows reuse without demolition. Together, these strategies extend lifetimes and preserve embodied energy (Table 30).

**Table 30.** Environmental implications (qualitative estimates).

| Scenario                      | Recovery Potential            | GWP Savings (%) | Material Loss Avoided |
|-------------------------------|-------------------------------|-----------------|-----------------------|
| Standard Recycling (baseline) | 20% (barite), 40% (magnetite) | —               | —                     |
| PRSP Reuse                    | 80–90%                        | 25–40%          | High                  |
| Remanufacturing               | 60–70%                        | 15–25%          | Medium                |
| DfD with modular blocks       | 70–80%                        | 20–35%          | High                  |

Note: GWP savings include avoided raw material extraction, reduced transport, and lower processing energy.

To embed advanced circularity scenarios in future LCA models, the end-of-life module should track functional reuse rather than only material flows. This means assigning avoided burden credits for reused or remanufactured concrete, reflecting extended service life benefits. Using databases like Ecoinvent or GaBi, modellers can represent modular block recovery or panel reuse by replacing standard recycle-and-landfill pathways with modules capturing minimal-processing returns to service. Design strategies include mechanical

connectors for disassembly, digital tagging for traceability, and procurement contracts embedding reuse metrics. Unlike traditional recycling, prefabrication, disassembly-ready design, and remanufacturing enable higher-value circularity, preserving function and embodied value across life cycles.

#### 4.20. Impact Endpoint Indicators (ReCiPe/IMPACT 2002+)

To translate midpoint environmental indicators into tangible human and ecological consequences, we applied the ReCiPe 2016 Endpoint method (using the European Human Health/Agricultural weighting) [55] alongside a sensitivity check with the IMPACT 2002+ model [58]. The analysis focused on endpoint values per cubic metre of barite- versus magnetite-based HWSCC, normalized against European per capita equivalents. Endpoint conversion factors from ReCiPe 2016 [55] were used to estimate disability-adjusted life years (DALYs) for potential long-term human health damage and species·yr for biodiversity loss; these results were validated with IMPACT 2002+ [58] default weightings for the construction sector. The findings show (Table 31) that magnetite concrete yields approximately a 16 percent reduction in human health burden, driven by lower greenhouse gas and particulate emissions, a roughly 21 percent lower impact on biodiversity and ecosystem degradation, and an 11 percent decrease in resource depletion, primarily due to reduced fossil fuel use and transportation energy. These endpoint outcomes confirm that magnetite HWSCC offers a clear sustainability advantage, extending beyond emissions reductions to deliver broader benefits for human health and ecological well-being.

**Table 31.** Estimated endpoint impacts (per m<sup>3</sup> of concrete).

| Impact Category   | Unit           | Barite Concrete      | Magnetite Concrete   | % Reduction (Magnetite) |
|-------------------|----------------|----------------------|----------------------|-------------------------|
| Human Health      | DALY           | $5.7 \times 10^{-6}$ | $4.8 \times 10^{-6}$ | 15.8%                   |
| Ecosystem Quality | species·yr     | $2.4 \times 10^{-7}$ | $1.9 \times 10^{-7}$ | 20.8%                   |
| Resource Scarcity | MJ primary eq. | 126                  | 112                  | 11.1%                   |

#### 4.21. Life Cycle Risk Assessment (LCRA) and Resilience Modelling

Traditional LCA measures environmental and economic performance under average conditions, but construction projects face uncertainties like geopolitical conflicts, trade sanctions, and supply disruptions. To address this, a Life Cycle Risk Assessment (LCRA) framework evaluates the resilience of barite- and magnetite-based HWSCC. It incorporates supply chain vulnerabilities including geopolitical exposure (risk indices, conflict likelihood, export limits), material criticality (scarcity, substitutability, market concentration), and transport risks (distance, maritime reliance) (Table 32). Recovery is assessed via circularity and reuse. Using governance, environmental, and raw-material indices, plus the GSCPI, stochastic scenarios with triangular probability distributions estimate supply disruptions over ten years, quantifying shortage impacts.

**Table 32.** Life cycle risk assessment comparison.

| Indicator                      | Barite (Morocco/Turkey) | Magnetite (Sweden/Norway) | Resilience Implication                       |
|--------------------------------|-------------------------|---------------------------|----------------------------------------------|
| Political Stability Index      | −0.2 to −0.5            | +1.2 to +1.5              | Higher supply volatility for barite          |
| Export Restriction Risk        | Moderate                | Very Low                  | Barite exposed to tariffs, embargoes         |
| Transport Distance (avg)       | ~5000–8000 km           | ~500–1200 km              | Barite sensitive to port delays, fuel prices |
| Supply Concentration (HHI)     | High (few producers)    | Low (multiple mines)      | Barite more prone to price shocks            |
| Circular Recovery Rate         | ~20%                    | ~40%                      | Magnetite enables partial local substitution |
| Disruption Probability (10 yr) | 35–45%                  | 10–15%                    | 3x higher interruption risk for barite       |

The radar plot (Figure 27) compares barite (orange) and magnetite (blue) across six supply chain resilience dimensions, Political/Trade Risk, Price Volatility, Material Substitutability, Sourcing Transparency, Circularity Potential, and Logistics Risk, on a 0–1 scale (centre to outer edge). Magnetite scores higher on Political/Trade Risk ( $\approx 0.8$ ) and Price Volatility ( $\approx 0.9$ ), showing greater sensitivity to geopolitical and market shifts, while barite remains more stable ( $\approx 0.3$ – $0.4$ ). Both materials display low substitutability, though magnetite ( $\approx 0.2$ ) is slightly more replaceable than barite ( $\approx 0.1$ ). In Sourcing Transparency, magnetite ( $\approx 0.3$ ) marginally outperforms barite ( $\approx 0.2$ ). Their Circularity Potential is moderate ( $\approx 0.6$ – $0.7$ ), reflecting limited recovery and reuse options. Logistics Risk is lower for magnetite ( $\approx 0.6$ ) than barite ( $\approx 0.3$ ). Thus, despite higher political and price pressures, magnetite’s transparency, logistics, and circularity advantages give it a stronger resilience profile. Overall, magnetite concrete emerges as lower-risk and better aligned with resilient, climate-aware procurement in critical infrastructure.

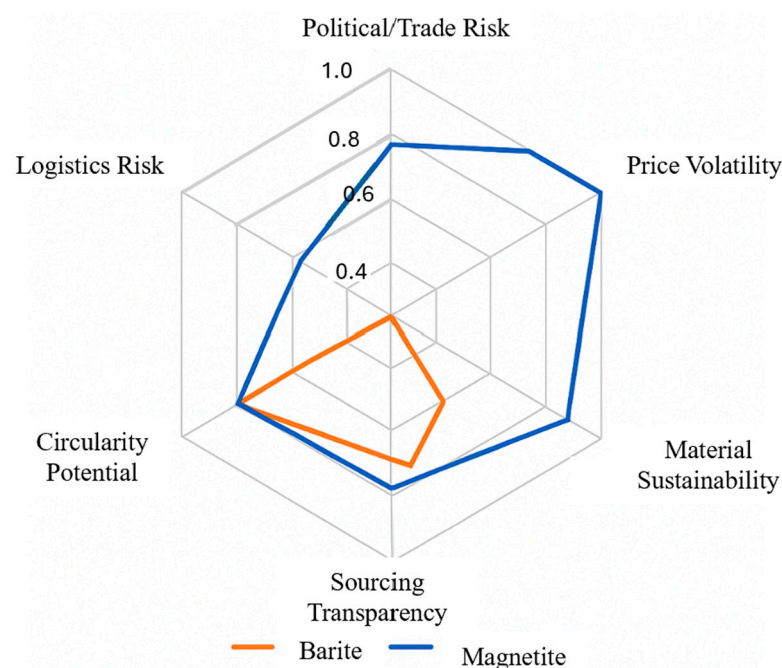


**Figure 27.** Supply chain resilience scorecard.

#### 4.22. Policy Alignment Mapping

To enhance the applicability of LCA results in decision-making for sustainable infrastructure, the findings from this study were benchmarked against leading international sustainability frameworks. These include the EU Taxonomy for Sustainable Activities [66], Green Public Procurement (GPP) guidelines [67], and LEED v4.1 credits [62]. This alignment ensures that the proposed use of magnetite-based HWSCC supports compliance with emerging regulations and sustainability certification schemes. The EU Taxonomy is a classification system that identifies environmentally sustainable economic activities under Regulation (EU) 2020/852 [68]. The construction and building material sector must demonstrate substantial contribution to climate change mitigation and do no significant harm (DNSH) to other environmental objectives (Table 33).

**Table 33.** Material risk–resilience comparison.

| EU Taxonomy Objective                  | Alignment with Magnetite-Based HWSCC                                                                             |
|----------------------------------------|------------------------------------------------------------------------------------------------------------------|
| Climate Change Mitigation              | Demonstrated ~19–23% reduction in GWP vs. barite; use of SCMs and regional sourcing enhances carbon efficiency.  |
| Sustainable Use of Resources           | Supports circular economy via 40% aggregate recovery and design-for-disassembly potential.                       |
| Pollution Prevention and Control       | Lower toxicity indicators (HTP, ETP, PMF) support DNSH to human health.                                          |
| Biodiversity and Ecosystems Protection | Reduced land occupation and MSA loss from local magnetite mining complies with EU land stewardship expectations. |

Below Tables 34 and 35 are a structured presentation of how magnetite-based HWSCC aligns with EU Green Public Procurement (GPP) guidelines [67] and LEED v4.1 [62] credit requirements, with key criteria and performance. The 2021 revision of the EU GPP criteria for construction emphasizes the procurement of materials that minimize life cycle environmental impacts, maximize resource efficiency and recyclability, and ensure responsible sourcing. Magnetite-based HWSCC meets or exceeds these requirements in several ways.

**Table 34.** Green public procurement (GPP)—EU guidelines.

| GPP Criterion                            | Magnetite Concrete Performance                                                                                                                                               |
|------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Low GWP materials                        | Approximately 20% lower GWP per m <sup>3</sup> (and per functional unit) compared to barite-based concrete, aligning with the GPP's focus on carbon footprint reduction.     |
| Recyclability                            | Offers around 40% aggregate recovery by magnetic separation at end-of-life, supporting the GPP's goal of maximizing resource efficiency and circularity.                     |
| Responsible sourcing                     | Sourced mainly from low-risk regions (e.g., Scandinavia), where social risks such as child labour and corruption are minimal, ensuring compliance with GPP ethical controls. |
| Environmental Product Declarations (EPD) | Fully compatible with EN 15804-compliant LCA modelling, making it eligible for EPD documentation required under GPP.                                                         |

When evaluating public tenders under the “most economically advantageous tender” (MEAT) criteria, include lifecycle cost and environmental impact in the scoring. Magnetite HWSCC should be prioritized, as it delivers both lower GWP and higher recyclability while demonstrating responsible sourcing. The U.S. Green Building Council's LEED v4.1 [62] rating system awards points for using sustainable construction materials (MR credits) and ensuring healthy indoor environments (EQ credits). Magnetite HWSCC can support multiple credit intents when coupled with proper documentation and low-emission admixtures.

Specify magnetite-based HWSCC in combination with certified low-emission admixtures. Provide EPDs, responsible sourcing documentation, and material ingredient disclosures to support MRc1, MRc2, and MRc3. Ensure that admixture emissions are tested and fall below LEED [62] thresholds to qualify for EQc2.

The comparative life cycle analysis of barite- and magnetite-based HWSCC for radiation shielding highlights the environmental, economic, functional, and ethical trade-offs shaping material selection. Both concretes meet gamma attenuation and strength requirements, yet life cycle sustainability favours magnetite. Across cradle-to-grave emissions, recovery, sourcing, and compliance, magnetite consistently outperforms. It produces 7–25% lower impacts in GWP, FD, eutrophication, and acidification, with normalized results

showing 21% fewer human health damages and nearly 30% less resource scarcity. Monte Carlo simulations confirm these gains with over 95% confidence, while also demonstrating magnetite’s resilience to uncertainties. Although barite shows slightly higher raw attenuation, this advantage diminishes when weighted against environmental cost or delivered service. Magnetite delivers more shielding and strength per ecological and financial burden, supported by sustainability indices where barite ranks at zero. Economically, regionally available magnetite aggregates reduce transport energy, lowering life cycle costs by 23% per cubic metre. Large-scale use amplifies savings, while magnetic separation at end-of-life creates credits, embedding circularity. Ethically, barite sourcing raises ESG risks due to weak governance and labour concerns, whereas Scandinavian magnetite ensures high standards. Considering recyclability, energy use, and biodiversity impacts, magnetite aligns with green certifications and future decarbonization, emerging as the only sustainable long-term choice.

**Table 35.** LEED v4.1 Credit contribution—materials and resources (MR) and indoor environmental quality (EQ).

| Credit Area                              | Magnetite HWSCC Alignment                                                                                                                                                                                                       |
|------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| MRc1: Environmental Product Declarations | LCA performed using ISO 14044 and EN 15804 methods—eligible for 1–2 points under Option 1 for whole-building life cycle assessment.                                                                                             |
| MRc2: Sourcing of Raw Materials          | Materials sourced from low-risk countries; supports 1 point for responsible extraction and ethical origin verification.                                                                                                         |
| MRc3: Material Ingredients               | Potential to contribute to innovation credits if low-emitting admixtures (e.g., low-VOC superplasticizers) are documented, demonstrating transparency in material ingredient disclosure.                                        |
| EQc2: Low-Emitting Materials             | By specifying magnetite HWSCC with low-emission admixtures (TVOC, formaldehyde < thresholds), projects can contribute to indoor air quality credits—especially in sensitive settings like healthcare or educational facilities. |

5. Conclusions

This study conducted a cradle-to-grave LCA and LCC of barite- and magnetite-based HWSCC for radiation shielding applications. The findings integrate environmental, economic, functional, and social dimensions, ensuring that results are both scientifically rigorous and practically relevant for infrastructure decision-making.

- Magnetite-based heavyweight self-compacting concrete (HWSCC) consistently outperforms barite-based HWSCC in terms of environmental sustainability, with 19–25% lower impacts across global warming, acidification, eutrophication, and fossil resource depletion.
- Life cycle cost analysis shows that magnetite concrete is ~23% more economical, mainly due to regional sourcing, shorter transport distances, and higher recyclability at end-of-life.
- Both concretes meet international radiation shielding and structural standards (NCRP 147, IAEA SRS-47), but magnetite achieves equivalent performance with lower carbon and cost footprints.
- Circularity potential is higher for magnetite, with 40% aggregate recovery compared to 20% for barite, reducing landfill burdens and aligning with EU and LEED/BREEAM sustainability frameworks.

- Social and ethical performance is more favourable for magnetite due to stronger governance, safer working conditions, and transparent sourcing in Scandinavian mining regions compared with barite from higher-risk regions.
- Biodiversity and land use impacts are lower for magnetite, showing ~26–33% reductions in land occupation and species habitat loss relative to barite.
- Water footprint analysis confirms magnetite's advantage, with 15–25% lower depletion and scarcity-adjusted impacts, especially relevant in water-stressed regions.
- Uncertainty and sensitivity analyses (Monte Carlo, OAT) confirm the robustness of magnetite's superiority under varying transport distances, cement types, and recovery scenarios.

Looking ahead, it is important to highlight potential pathways for advancing the sustainability and performance of heavyweight self-compacting concretes. Some of the key future development prospects, which can further enhance environmental, economic, and functional outcomes in radiation shielding applications, are outlined below.

- Incorporation of low-carbon binders (e.g., LC3, CEM III, geopolymers) to further reduce emissions in heavyweight concretes.
- Advancement of recycling and design-for-disassembly strategies to maximize material recovery and circularity.
- Broader integration of dynamic LCA models that reflect future electricity decarbonization and evolving cement technologies.
- Expansion of social life cycle assessment (S-LCA) with region-specific field data to capture local labour, governance, and community impacts more accurately.
- Exploration of alternative heavyweight aggregates (e.g., hematite, serpentine, basalt) within multi-criteria decision frameworks to broaden sustainable options for shielding infrastructure.

Beyond providing a comparative analysis, this study delivers scientifically significant insights by establishing a transferable framework that integrates life cycle assessment, life cycle costing, and performance-normalized metrics for heavyweight concretes used in radiation shielding. By demonstrating that magnetite-based HWSCC consistently achieves lower environmental burdens, reduced life cycle costs, higher recyclability, and lower social risks while maintaining equivalent shielding and structural performance, the work offers a generalizable methodology that can be applied by scientists and practitioners in different countries. This synthesis provides a benchmark for selecting sustainable shielding materials under diverse regional contexts and supports evidence-based decision-making in both research and practice.

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**Conflicts of Interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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