



# Life Cycle Impact Assessment for Steel Slag Aggregates Production in Abu Dhabi, United Arab Emirates

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## Abstract

Steel slag aggregates (SSA) offer a potential route for reducing reliance on natural aggregates (NA) and diverting steelmaking by-products from landfill. However, facility-specific life cycle data for SSA production in Abu Dhabi, United Arab Emirates, remain limited. This study quantifies the cradle-to-gate greenhouse gas footprint of SSA produced at two recycling facilities in Abu Dhabi. The assessment follows ISO 14040/14044 and uses a functional unit of 1 tonne of SSA. Primary 2024 operational data were combined with emission factors from the UK Government 2024 dataset, Intergovernmental Panel on Climate Change default values, and published literature. The combined emissions for 500,000 tonnes of SSA were 3,270.22 t CO<sub>2</sub>eq, corresponding to an average intensity of 6.54 kg CO<sub>2</sub>eq/tonne SSA. Al Fayah emitted 2,007.88 t CO<sub>2</sub>eq for 250,000 tonnes of output, equivalent to 8.03 kg CO<sub>2</sub>eq/tonne SSA, while KEZAD B emitted 1,262.33 t CO<sub>2</sub>eq for 250,000 tonnes of output, equivalent to 5.05 kg CO<sub>2</sub>eq/tonne SSA. Inbound material transportation dominated the footprint at both plants, particularly last-mile road transport. Compared with the NA benchmark of 7.75 kg CO<sub>2</sub>eq/tonne, the average SSA intensity was approximately 16% lower. Under the stated boundary and assumptions, SSA showed lower cradle-to-gate emissions than NA. The way forward should prioritize primary metering, carrier data, and the development of a third-party-verified Environmental Product Declaration to strengthen comparability and market uptake.

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## Keywords

*Steel slag aggregates, life cycle assessment, circular economy*

## 1. Introduction

Climate change has emerged as one of the most pressing global challenges of the 21<sup>st</sup> century. Rising concentrations of greenhouse gases (GHGs) have escalated global warming and climate change. In the United Arab Emirates (UAE), total GHG emissions increased by 174% between 1994 and 2014, rising from 74 million to more than 200 million t CO<sub>2</sub>eq (CO<sub>2</sub> equivalent) (Ministry of Climate Change and Environment, 2016). This escalation was mainly driven by robust economic growth and an expanding population, underscoring the urgent need for sustainable strategies to mitigate environmental impacts while supporting continued development.

Within this context, the construction sector plays a pivotal role, given its heavy dependence on energy-intensive materials such as cement and natural aggregates (NA). Cement is responsible for approximately 8% of the world's CO<sub>2</sub> emissions due to its calcination and fuel combustion processes. Meanwhile, NA extraction depletes non-renewable resources and disrupts ecosystems (Bawab et al., 2025; Hwalla et al., 2025). Recent research underscores the pressing need to adopt sustainable alternatives, including the valorization of industrial byproducts and the integration of recycled materials into construction applications (Liu et al., 2024; Ma et al., 2025).

Steel slag, a calcium-rich byproduct of the steelmaking process, represents another promising resource for sustainability. Globally, steelmaking generates millions of tonnes of slag annually, much of which is landfilled, leading to environmental risks. (Najm et al., 2021). Slag waste can be repurposed in many ways; for instance, steel slag carbonation, a carbon capture, utilization, and storage application, can achieve carbon-negative outcomes with a global warming potential (GWP) of  $-76.8$  kg CO<sub>2</sub>eq/tonne slag. (Li et al., 2024), which highlights its potential as a strategy for both waste management and emissions reduction. Beyond carbonation, steel slag can be processed into steel slag aggregates (SSA) suitable for road construction and concrete, providing a dual advantage of resource conservation and climate impact mitigation, though technical barriers such as variability and durability must be addressed (Alzard et al., 2021; Lan et al., 2025; Soliman et al., 2025).

As aggregate demand for mega projects grows, regulations increasingly require the industry to align with Abu Dhabi's sustainability agenda under the UAE Net Zero 2050 strategy (Ministry of Energy & Infrastructure, 2023). Against this background, a clear research gap exists. To the authors' knowledge, no peer-reviewed, region-specific, primary-data LCA of the SSA production process has been reported for Abu Dhabi, and the relative contribution of imported-feedstock logistics versus on-site processing has not been quantified for Gulf conditions. Addressing this gap, the present study provides a facility-level, primary-data cradle-to-gate LCA of SSA production in the Emirate. The specific objectives are to: (i) quantify the cradle-to-gate GHG footprint of SSA at two Abu Dhabi facilities across Scopes 1–3, expressed per tonne of SSA; (ii) identify the dominant emission contributors, including materials versus transport and transport by mode; (iii) benchmark the result against the NA reference value under a common factor set; and (iv) evaluate result robustness through sensitivity and data-quality analysis and outline a pathway to a verified EPD.

## 2. Methodology

This study follows the four ISO 14040/14044 phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. Methods and data are reported consistently with these standards.

### 2.1. Goal and Scope

The goal of this LCA is to quantify the environmental impact of SSA production at two recycling facilities in Abu Dhabi, UAE, and to compare it with the footprint of NA to inform its adoption in construction and corporate environmental reporting.

The functional unit is 1 tonne of SSA produced; all results are normalised to this unit. A cradle-to-gate system boundary is adopted (**Figure 1**), spanning slag-feedstock acquisition and transport (local and imported), processing (crushing, screening, and magnetic separation), internal handling and stockpiling, and ancillary operations (dust suppression, equipment operation, and maintenance-related transport). The process description was provided by Mawaad Environmental Services, which operates both plants.

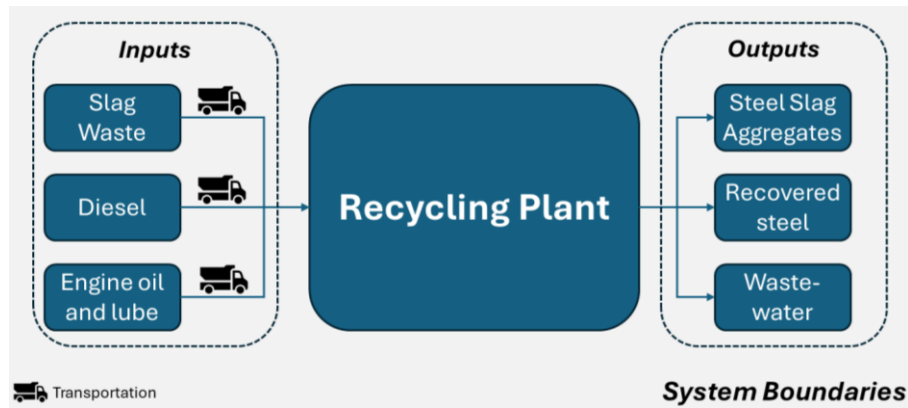


Figure 1. System boundaries considered in this study.

## 2.2. Data Sources and Data Quality

All foreground data represent calendar year 2024 and were obtained directly from Mawaad Environmental Services. Diesel and engine oil consumption were taken from procurement and fuel-dispensing records; water use was taken from utility/abstraction records; annual SSA output and the slag-feedstock split were taken from production logs; and transport distances were derived from fixed origin–destination routes (supplier sites, Khalifa Port, and Musaffah) using road-network and nautical distances. No foreground quantity was estimated where a metered or recorded value existed; the only modeled quantities are the transport activity values (tonne-kilometers), computed from recorded masses and fixed route distances as described in Section 2.4. Background emission factors are secondary data from the Department for Environment, Food & Rural Affairs[DEFRA](2024), IPCC defaults, and published literature.

To evaluate the robustness of the results, a one-at-a-time sensitivity analysis was conducted for the parameters expected to have the greatest influence on the combined SSA intensity: road transport distance, HGV payload/load factor, marine-freight emission factor, and diesel combustion emission factor. Each parameter was varied by  $\pm 25\%$  relative to the baseline while holding the other parameters constant. The sensitivity analysis was performed on the combined cradle-to-gate intensity and is reported in Section 3.3 together with a qualitative data-quality assessment.

## 2.3. System Boundary, Allocation, and Justified Exclusions

The two facilities produce two outputs: SSA (the product under study) and recovered ferrous metal, which is returned to steel mills. A cut-off (recycled-content) approach was applied: the recovered metal leaves the system as a recyclable co-product. Under this approach, no upstream burden was assigned to the recovered metal beyond the system boundary, and no mass or economic allocation was applied to the SSA footprint. GWP, expressed in t CO<sub>2</sub>eq, is the reported impact category, consistent with prior work identifying it as the dominant category for aggregate production (Alzard et al., 2021).

Multiple assumptions were made to conduct this study. These assumptions include:

All electricity consumed in the plant is generated on-site by diesel generators; no grid electricity is used.

Total SSA production of 500,000 tonnes is achieved through two facilities: Al Fayah and KEZAD B.

50% of processed slag feedstock processed at the Al Fayah plant is imported from Qatar via sea route, and 50% is sourced locally from Musaffah. Transportation impacts are considered only for inbound loads; return trips are excluded. Maintenance materials and diesel are sourced from Musaffah. The transportation distances considered are listed in **Table 1**. The maintenance of transportation vehicles is excluded. Transport of recovered metal scrap is excluded from this LCA.

Table 1. Transportation distances considered in this study.

Plant	Material	Trip	Mode	Distance (km)
Al Fayah	Slag waste	Qatar to Khalifa Port	Marine transport	431

	Slag waste	Khalifa Port to plant	Road transport	75
	Slag waste	Musaffah to plant	Road transport	60
	Engine Oil and Lube	Musaffah to plant	Road transport	60
	Diesel	Musaffah to plant	Road transport	60
KEZAD B	Slag waste	Khalifa Port to plant	Road transport	25
	Engine Oil and Lube	Musaffah to plant	Road transport	71
	Diesel	Musaffah to plant	Road transport	71

Intergovernmental Panel on Climate Change (IPCC) and GHG Conversion Factors 2024 are used to calculate the impact of both transportation modes.

Return (empty) trips were excluded because the DEFRA “average laden” tonne-kilometer factors already embed fleet-average empty-running; separately adding back-hauls would double-count. This avoids potential double-counting when average-laden factors are used and is examined in the sensitivity analysis.

Transport of recovered metal was excluded, consistent with the cut-off treatment of the recovered co-product, whose downstream handling belongs to the steelmaking system.

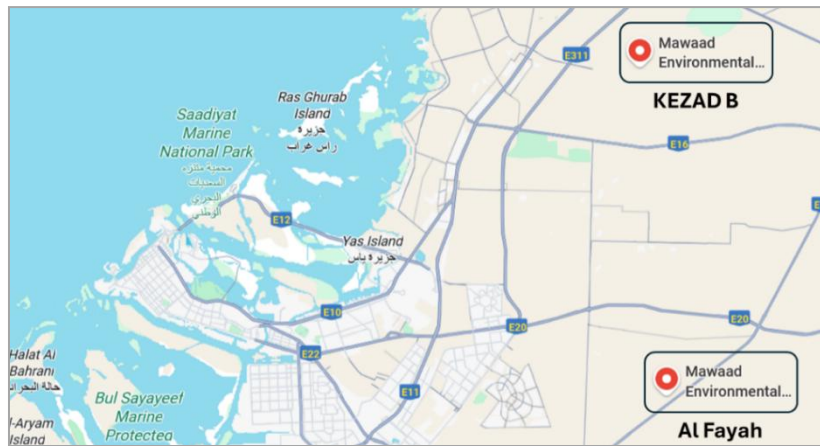
Vehicle manufacture and maintenance were excluded as capital goods/secondary processes that are typically negligible relative to operational fuel and freight in cradle-to-gate aggregate LCAs.

Downstream distribution, the use phase, and end-of-life were excluded by definition of the cradle-to-gate boundary because they depend on application-specific decisions outside the producer’s control.

## 2.4. Life Cycle Inventory (LCI)

### 2.4.1. Facility Locations and Process Overview

The two facilities considered for this study are Al Fayah and KEZAD B recycling plants, which Mawaad Environmental Services operates (**Figure 2**). The sites convert electric arc furnace slag into SSA and recover embedded ferrous metal for return to steelmakers. The combined nominal output equals 500,000 tonnes of aggregates per year, with production shared between the two plants. Each site runs a dedicated line that includes reception and storage pads, a scalper, a vibrating grizzly, primary magnetic separation, size reduction through jaw and impact crushers, multi-deck screening to final product sizes below 19 mm, and secondary magnetic separation. Conveyors, transfer points, and stockpiles are fitted with water-spray dust suppression and skirt sealing. Power is supplied on-site by a diesel generator. Finished SSAs are stockpiled in graded bays for dispatch to customers, while steel mills collect recovered metal separately. This section provides the operational context for the LCI and subsequent results.



**Figure 2.** Mawaad Environmental Services' recycling plants' location

Source: Google Maps, 2025.

### 2.4.2. LCI Analysis

The combination of modern equipment and operational controls enables the recycling plants to achieve high plant availability (>90%), superior metal recovery rates (up to 80% weighted average), and consistently high-quality aggregates that meet market requirements. The inventory compiles 2024 primary activity data from both plants and matches them to corresponding emission factors, as shown in **Table 2**. The study treats diesel combustion on-site for power as Scope 1. Water treatment, engine oil, and all inbound logistics are considered Scope 3 upstream emissions. No Scope 2 applies because the plants do not consume grid electricity. Scope definitions and category mapping align with the GHG Protocol Scope 3 guidance for Category 4 upstream transportation and distribution. (Greenhouse Gas Protocol, 2013).

As mentioned earlier, the company produced 500,000 tonnes of SSA in 2024, with an equal split between Al Fayah and KEZAD B. Each plant consumed 113,562.355 litres of diesel, 1,200 litres of engine oil, and 340.69 m<sup>3</sup> of water. Inbound slag to Al Fayah comprised a 50/50 mass split between Qatar shipments and a local supplier. Qatar shipments travelled 431 km by bulk carrier and then 75 km by road; the local supplier delivered 60 km by road from Musaffah. KEZAD B received all slag from Qatar via a 431 km sea route and a 25 km road route. These distances reflect one-way loaded movements only.

**Table 2.** Material use contributes to the overall environmental impact.

Plant	Input	Quantity	Unit	EF (kg CO <sub>2</sub> eq/unit)	EF Source
Al Fayah	Diesel	113,562.4	L	2.7	(DEFRA, 2024)
	Engine oil	1,200	L	0.89635	(Intergovernmental Panel on Climate Change[IPCC], n.d.; Raimondi et al., 2012)
	Water	340.69	m <sup>3</sup>	0.149	(IPCC, n.d.)
KEZAD B	Diesel	113,562.4	L	2.7	(DEFRA, 2024)
	Engine oil	1,200	L	0.89635	(IPCC, n.d.; Raimondi et al., 2012)
	Water	340.69	m <sup>3</sup>	0.149	(IPCC, n.d.)

### 2.4.3. Emission Factors and Justification of DEFRA Use in a UAE Context

Transport was characterized by DEFRA (2024) factors: “articulated >33 t, average laden” road freight at 0.08617 kg CO<sub>2</sub>eq/tonne-km and “bulk carrier, average” marine freight at 0.00354 kg CO<sub>2</sub>eq/tonne-km. Diesel combustion used 2.70 kg CO<sub>2</sub>eq/L based on fuel carbon content (DEFRA, 2024). Activity for each leg was computed as tonne-kilometers = mass moved × one-way distance; for example, the Qatar–port sea leg for Al Fayah is 128,750 t × 431 km, and for KEZAD B, 257,500 t × 431 km (**Table 3**).

DEFRA factors were adopted for three reasons. First, no peer-reviewed, UAE-specific tonne-kilometer or fuel factors are currently published; national technical work indicates such factors are still under development and recommends consistent international methods in the interim. (Abu Dhabi Quality and Conformity Council, 2015; U.S. Energy Information Administration, 2022). Second, DEFRA factors are transparent, widely used internationally, and updated annually, supporting comparability and reproducibility. (Li et al., 2022; Muñoz-Arango et al., 2025). Third, the diesel combustion factor is governed primarily by fuel carbon content, a fuel property that transfers reasonably to UAE diesel. The principal limitation is that DEFRA road factors reflect a UK fleet and load profile, which may differ from those in the UAE; because the footprint is transport-dominated, this is the largest source of geographical uncertainty and is therefore examined in Section 3.3. Crucially, grid-electricity factors, where UK/UAE divergence would be greatest, are not used, as all power is on-site diesel. These secondary factors are intended to be replaced by carrier-specific and UAE-specific data as they mature.

**Table 3.** Summary of transportation distances considered and their emission factors.

Plant	Description	Vehicle	Activity (tonne-km)		EF (kg CO <sub>2</sub> eq/tonne-km)
			Distance (km)	Weight (tonne)	
Al Fayah	Waste transport	Bulk carrier	431	128750	0.00354
		HGV articulated >33t avg laden	75	128750	0.08617
		HGV articulated >33t avg laden	60	128750	0.08617
	Engine oil and lubricants transport	HGV articulated >33t avg laden	60	1056	0.08617
	Diesel transport	HGV articulated >33t avg laden	60	94.48	0.08617
KEZAD B	Waste transport	Bulk carrier	431	257500	0.00354
		HGV articulated >33t avg laden	25	257500	0.08617
	Engine oil and lubricants transport	HGV articulated >33t avg laden	71	1056	0.08617
	Diesel transport	HGV articulated >33t avg laden	71	94.48	0.08617

Wastewater from both plants equals the annual water use, since no water is recycled in the recycling plants. As shown in **Table 4**, Al Fayah generated 340.69 m<sup>3</sup> of wastewater in 2024. KEZAD B generated the same volume and the same impact. Combined wastewater treatment remains reported in Scope 3 upstream in line with the GHG Protocol’s Category 5 treatment of waste generated in operations.

**Table 4.** Wastewater emission factors.

Plant	Output	Quantity	Unit	EF (kg CO <sub>2</sub> eq/unit)
Al Fayah	Wastewater	340.69	m <sup>3</sup>	0.18574
KEZAD B	Wastewater	340.69	m <sup>3</sup>	0.18574

### 3. Results and Discussion

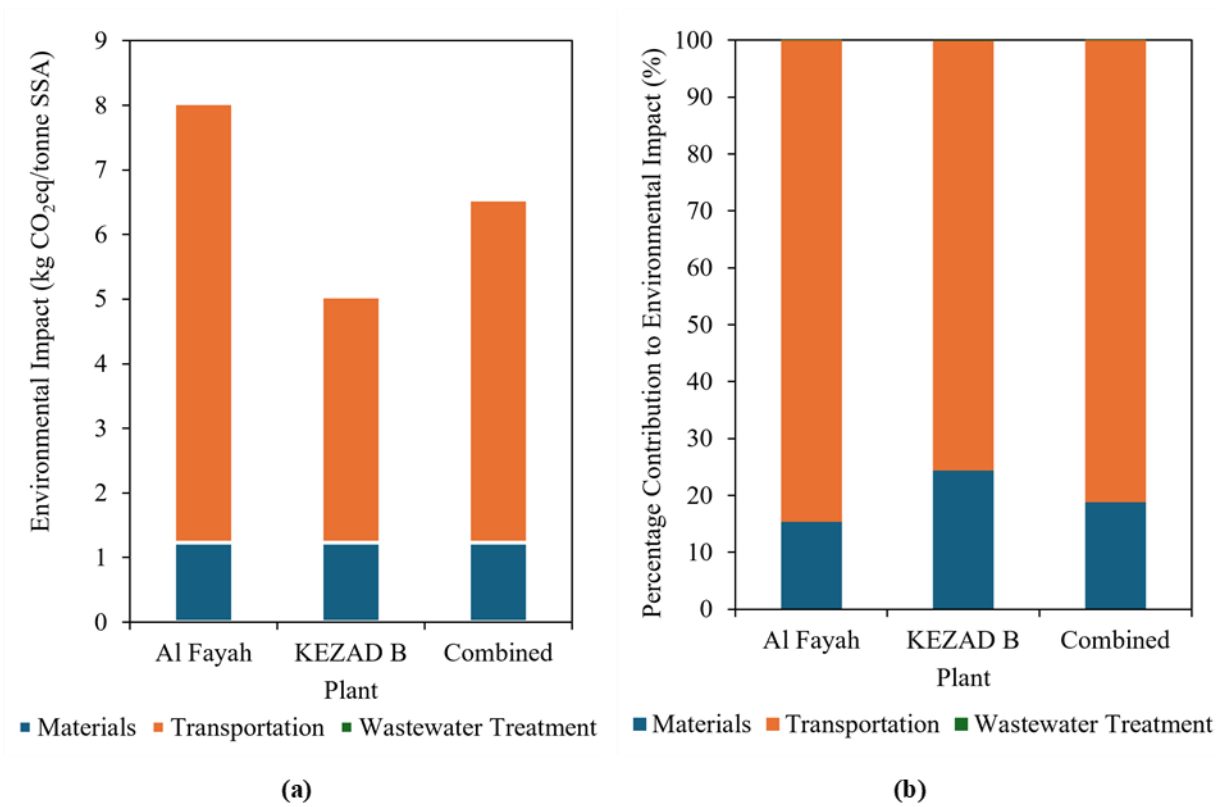
#### 3.1. Life Cycle Impact Assessment (LCIA)

Throughout the Results and Discussion section, total GHG emissions are reported in t CO<sub>2</sub>eq, emission intensities are reported in kg CO<sub>2</sub>eq/tonne SSA, and freight emission factors are reported in kg CO<sub>2</sub>eq/tonne-km. Under the emission factors described in Section 2.4.3, Al Fayah reports 307.75 t CO<sub>2</sub>eq from materials, 1,700.07 t CO<sub>2</sub>eq from inbound logistics, and 0.0632 t CO<sub>2</sub>eq from wastewater treatment, for a total of 2,007.88 t CO<sub>2</sub>eq and an intensity of 8.03 kg CO<sub>2</sub>eq/tonne SSA. KEZAD B reports 307.75 t CO<sub>2</sub>eq from materials, 953.43 t CO<sub>2</sub>eq from inbound logistics, and 0.0632 t CO<sub>2</sub>eq from wastewater treatment, for a total of 1,262.33 t CO<sub>2</sub>eq and an intensity of 5.05 kg CO<sub>2</sub>eq/tonne SSA. Combined, the two plants total 3,270.22 t CO<sub>2</sub>eq for 500,000 tonnes of SSA, yielding an average intensity of 6.54 kg CO<sub>2</sub>eq/tonne SSA. **Table 5** presents a summary of the results.

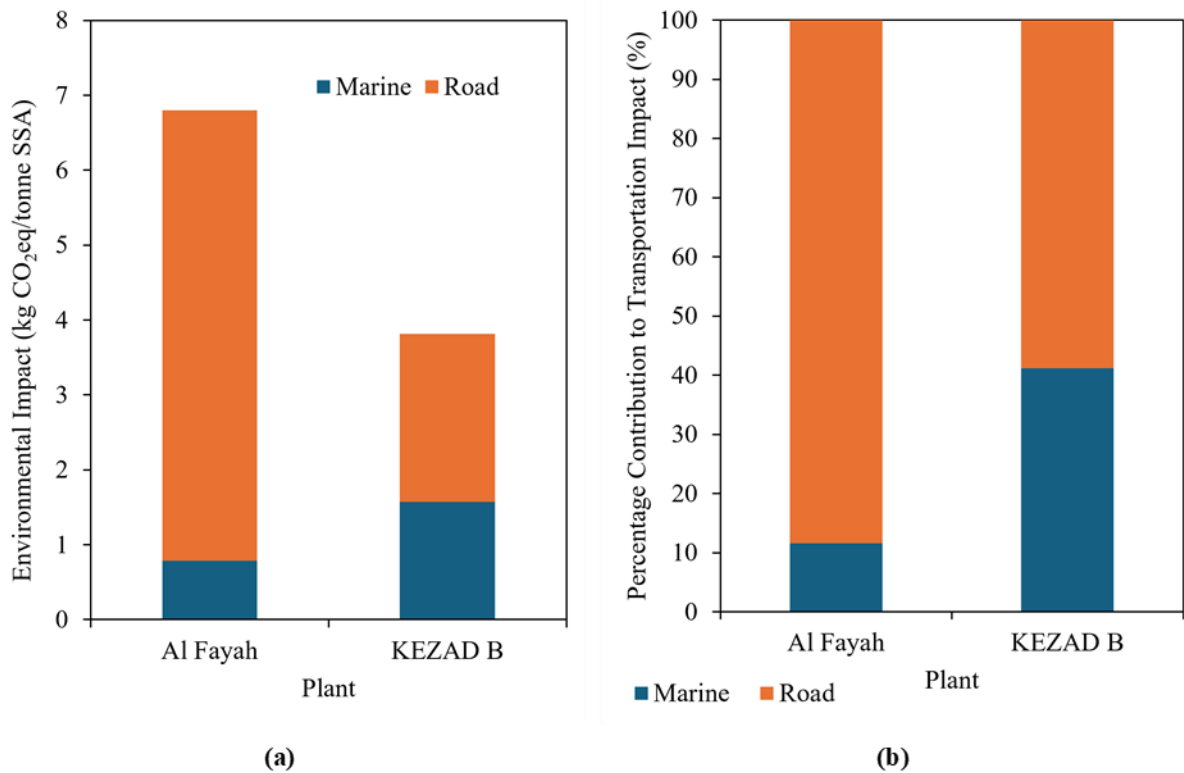
**Table 5.** The environmental impact of materials, transportation, and wastewater treatment for each plant.

Plant	Environmental Impact (t CO <sub>2</sub> eq)			Total	Intensity (kg CO <sub>2</sub> eq/tonne SSA)
	Materials	Transportation	Wastewater Treatment		
Al Fayah	307.75	1,700.07	0.0632	2,007.88	8.03
KEZAD B	307.75	953.43	0.0632	1,262.33	5.05
Combined	615.49	2,654.60	0.1266	3,270.22	6.54

The stacked bar chart presented in **Figure 3** illustrates the dominance of transport over materials at both plants, with the effect being more pronounced at Al Fayah due to its longer road legs. The transport-by-mode presented in **Figure 4** shows that road movements account for 88% of Al Fayah's transport GWP and almost 59% at KEZAD B, reflecting each plant's last-mile distance.



**Figure 3.** Contribution of materials, transportation, and wastewater treatment to the cradle-to-gate GHG footprint of SSA production at Al Fayah and KEZAD B: (a) absolute contribution in t CO<sub>2</sub>eq and (b) percentage contribution to total plant-level emissions.



**Figure 4.** Contribution of road and marine transport to transport-related GHG emissions at Al Fayah and KEZAD B: (a) absolute contribution in t CO<sub>2</sub>eq and (b) percentage contribution to total transport emissions.

### 3.2. Interpretation

The calculations adhere to the ISO 14040/14044 structure for inventory compilation, ensuring that data, factors, and boundaries are transparent for subsequent impact assessment and interpretation. The Scope 3 Category 4 mapping and methods adhere to the GHG Protocol technical guidance. (Greenhouse Gas Protocol, 2013). For market context, DEFRA (2024) lists NA at 7.75 kg CO<sub>2</sub>eq/tonne. Benchmarking against this value, the modelled SSA intensity of 6.54 kg CO<sub>2</sub>eq/tonne is roughly 16% lower on a cradle-to-gate basis under the same factor set.

Road freight is the primary driver of GWP. At Al Fayah, road transportation accounts for approximately 88% of transport emissions. At KEZAD B, the road accounts for about 59%. Marine shipments help reduce intensity, but the last-mile road legs still control the totals, especially where distances are longer. Scope 1 diesel for on-site generation is the largest materials-related source. Engine oil and water treatment are minor contributors in comparison. These findings are consistent with DEFRA factors and the GHG Protocol approach to upstream logistics.

The transportation contribution to the overall environmental impact can be reduced by shifting more inbound mass to sea where feasible, shortening last-mile distances through routing, and prioritizing higher-capacity vehicles that match the articulated HGV profile used in the model. The recycling plants' operating company can also work with carriers to validate actual vehicle classes and load factors and update tonne-km factors accordingly. These steps ensure that the methods align with the GHG Protocol's Scope 3 calculation guidance and DEFRA documentation, while also improving representativeness. Scope 1 intensity could be reduced by improving generator efficiency or, where practical, integrating on-site renewable energy. Recording generator operating hours and average load would also allow the development of a kWh-based indicator for future audits.

The results are consistent with previous LCA studies showing that the environmental benefit of recycled or secondary aggregates depends strongly on system boundary, transport distance, and the avoided use of virgin quarry materials. A study by Sousa et al. (2026) reported an emission intensity of 6.64 kg CO<sub>2</sub>eq/tonne RA for recycled aggregate production, which is nearly identical to the SSA value reported in this study (Sousa et al., 2026). This high similarity in the reported values is probably due to the additional processing (crushing, sorting) both aggregates require, potentially high diesel/electricity use, and the substantial transport. Alzard et al. (2021) reported that replacing NA with RA in UAE concrete mixtures can improve environmental performance, although the magnitude of the benefit depends on the full concrete mix design and associated binder contributions.

Similarly, Loureiro et al. (2022) highlighted the potential of steel slag and recycled concrete aggregates to reduce reliance on quarry materials in asphalt applications, while emphasizing that environmental performance is affected by processing and transport requirements. In the present study, the average SSA intensity of 6.54 kg CO<sub>2</sub>eq/tonne SSA is below the DEFRA 2024 natural aggregate benchmark of 7.75 kg CO<sub>2</sub>eq/tonne under the same factor set. However, the plant-level results show that this advantage is not uniform: KEZAD B performs better due to the shorter last-mile road distance, whereas Al Fayah has a higher intensity due to longer road transport. Therefore, the findings are broadly consistent with earlier recycled-aggregate studies but also show that regional logistics and facility location are decisive factors in determining whether SSA provides a lower-carbon aggregate option.

It is worth mentioning that steel slag is commonly managed as inert or construction-type waste when landfilled. DEFRA's 2024 waste factors list inert mineral streams, such as aggregates, bricks, and concrete, at approximately 1.234 kg CO<sub>2</sub>eq/tonne for landfill, reflecting site operations and negligible methane formation. Using this factor for steel slag, diverting 515,000 tonnes of steel waste from landfill in 2024 avoids approximately 635,510 kg CO<sub>2</sub>eq, equal to 635.51 t CO<sub>2</sub>eq. This avoided burden equals about 20% of the modeled SSA cradle-to-gate footprint of 3,270.22 t CO<sub>2</sub>eq under the factor set used in this study. DEFRA cautions that waste factors are provided for accounting purposes and may not represent full comparative life-cycle outcomes; the estimate is therefore presented as a contextual indicator, not included in the main LCA result.

Recycling steel slag prevents material from entering landfills, recovers metal, and returns the mineral fraction to construction, thereby increasing resource efficiency and supporting a circular economy. The World Steel Association notes that co-product use prevents landfills and reduces CO<sub>2</sub> emissions. (World Steel Association, 2020). Substituting slag for natural aggregates also eases pressure on sand and gravel extraction, which the United Nations Environment

Program links to erosion, biodiversity loss, and other impacts. (United Nations Environment Programme, 2022). Studies on using by-products as aggregates report environmental gains from reduced virgin extraction and avoided disposal (Loureiro et al., 2022).

### 3.3. Sensitivity and Uncertainty Analysis

Because transportation accounted for approximately 81% of the combined cradle-to-gate footprint, a one-at-a-time (OAT) sensitivity analysis was conducted for the parameters with the greatest influence and uncertainty. The tested parameters were road transport distance, HGV payload/load factor, marine-freight emission factor, and diesel combustion emission factor. In each case, one parameter was varied while all other parameters were held constant at their baseline values. Continuous parameters were varied by  $\pm 25\%$ . The resulting change in the combined baseline intensity of 6.54 kg CO<sub>2</sub>eq/tonne SSA is reported in **Table 6**.

**Table 6.** One-at-a-time sensitivity of the combined SSA intensity (kg CO<sub>2</sub>eq/tonne SSA) and qualitative data-quality assessment.

Parameter varied	-25% case	+25% case	Approximate swing	Data-quality rating
Road one-way distance	5.51	7.57	-16% to +16%	Good (fixed routes)
HGV payload/load factor	8.31	5.48	+27% to -16%	Fair (fleet-average)
Marine-freight factor	6.25	6.84	$\pm 4\%$	Good (DEFRA)
Diesel factor	6.23	6.85	$\pm 5\%$	Good (fuel-based)

The results show that the combined SSA intensity is most sensitive to road transport distance and HGV payload/load assumptions, which is consistent with the dominance of last-mile road haulage in the inventory. In contrast, the marine freight and diesel combustion factors produce smaller changes in the combined result. The sensitivity analysis, therefore, confirms that the main uncertainty lies in freight assumptions, particularly road transport distance and loading conditions. Although the SSA intensity remains below the natural aggregate benchmark in several sensitivity cases, the margin narrows and may reverse under unfavorable road-freight assumptions. These findings reinforce the importance of obtaining carrier-specific data on actual payloads, routing, and return-trip conditions in future updates.

The qualitative data-quality assessment indicates good temporal representativeness because all foreground data refer to the 2024 reporting year, and good technological representativeness because the data were obtained from the two facilities under study. The main limitation is the geographical representativeness of the secondary transport emission factors, which are based on the UK Government 2024 dataset rather than UAE-specific freight factors. Accordingly, the results should be interpreted as representative of the stated facilities, year, boundary, and emission-factor set, rather than as a generic emission factor for all SSA production conditions.

### 3.4. The Way Forward

A practical way forward centres on stronger primary data and standardized accounting. Future work should meter generator output and diesel consumption to express on-site energy as kg CO<sub>2</sub>eq per kWh, which will improve traceability within the ISO 14040 framework. (International Organization for Standardization [ISO], 2020). Suppliers should contribute towards shifting the inbound logistics from generic distance-based factors to carrier data by actively engaging in capturing the actual vehicle classes, payloads, and routing from hauliers. Until robust UAE-specific factors are available, transport emissions can remain anchored to the UK Government 2024 conversion factors while documenting assumptions and data quality. (DEFRA, 2024). Additionally, for logistics, adopting the Smart Freight Centre's Global Logistics Emission Council Framework enables alignment with widely used freight reporting practices and eases integration of carrier data; accounting under the GHG Protocol remains the reference for boundary and category mapping. (Smart Freight Centre, 2025). These steps maintain consistency with ISO 14040/14044 while incrementally replacing secondary factors with primary measurements and verified activity data.

The results can support multiple decisions and disclosures. Projects and tenders can reference the quantified cradle-to-gate intensities when specifying aggregates, while scenario analysis explores route optimization, higher-capacity vehicles, and modal choices to reduce tonne-kilometres. Additionally, this study can be extended to a third-party verified Environmental Product Declaration (EPD) to communicate performance in the construction market. This pathway formalizes data quality control and comparability, positioning the product for green procurement. Periodic updates should refresh factor sets and recalculate intensities as new carrier data, operational metering, or local factors become available. Over time, uncertainty and sensitivity analyses can be expanded to quantify the influence of fleet mix, load factors, and seasonal operations, while keeping interpretation within the ISO four-phase structure. These actions convert this LCA from a one-off assessment into a living dataset that supports procurement, supplier engagement, and transparent reporting across reporting cycles.

#### **4. Conclusion**

This study applied the ISO 14040/14044 framework to a cradle-to-gate LCA of steel slag aggregates (SSA) produced in 2024 at two recycling plants operated by Mawaad Environmental Services in Abu Dhabi, UAE. The assessment used a functional unit of 1 tonne of SSA and mapped emissions in accordance with the GHG Protocol. Primary operational data from the two facilities were combined with secondary emission factors to quantify the greenhouse gas footprint of SSA production under the stated system boundary and assumptions.

The results show a combined GWP of 3,270.22 t CO<sub>2</sub>eq for 500,000 tonnes of SSA, corresponding to an average intensity of 6.54 kg CO<sub>2</sub>eq/tonne SSA. Al Fayah reported 2,007.88 t CO<sub>2</sub>eq for 250,000 tonnes of output, equal to 8.03 kg CO<sub>2</sub>eq/tonne SSA, while KEZAD B reported 1,262.33 t CO<sub>2</sub>eq for 250,000 tonnes of output, equal to 5.05 kg CO<sub>2</sub>eq/tonne SSA. Transportation was the dominant contributor at both facilities, with road haulage and last-mile distance explaining much of the difference between plants. Compared with the natural aggregate benchmark of 7.75 kg CO<sub>2</sub>eq/tonne under the same factor set, the average SSA intensity was approximately 16% lower.

These findings indicate that SSA can provide a lower-carbon aggregate option under the conditions assessed in this study. However, the result should not be generalized without considering local logistics, feedstock origin, vehicle loading, emission-factor selection, and plant operating conditions. The study is limited to two facilities and one reporting year, and it relies partly on secondary emission factors in the absence of UAE-specific freight data. Future work should therefore prioritize carrier-specific transport data, direct metering of energy use, expanded uncertainty analysis, and third-party verified Environmental Product Declarations to improve comparability and support wider market adoption.

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#### **Ethics Approval**

Not applicable.

#### **Conflict of Interest**

The author(s) declare(s) that there is no competing interest.

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