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Fuel Substitution in Cement Production: A Comparative Life Cycle Assessment of Refuse-Derived Fuel and Coal

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Abstract

Cement production in Africa remains carbon-intensive, primarily due to the use of coal-based thermal energy. This study conducts a comparative cradle-to-gate life cycle assessment (LCA) of cement production using 100% coal (Scenario A) against partial substitution with refuse-derived fuel (RDF) at a 20% thermal input rate (Scenario B), with case studies in South Africa and Ethiopia. The LCA, modeled in SimaPro 9.2.0.1 with Ecoinvent v3.7.1 and regional data, evaluates midpoint environmental impacts across the following five stages: raw materials, clinker production, electricity, fuel use, and transportation. The results show that Scenario B reduces the global warming potential (GWP) by 3.3–4.2% per kg of cement, with minimal increases in other impact categories. When avoided landfill methane is accounted for, GWP reduction improves to 6.7%. Fossil resource depletion drops by 10%, and toxicity and particulate emissions show marginal improvements. Economic analysis under South Africa's 2025 carbon policy reveals a modest net cost increase of $2–3 per ton of cement and an abatement cost of $64–87 per ton of CO_2. The study provides new insights by harmonizing LCA models across national contexts, linking emissions reductions to economic instruments, and quantifying the co-benefits of RDF for waste management. The results support RDF co-processing as a scalable mitigation strategy for the African cement sector, recommending substitution rates of 15–30%, policy alignment, and enhancement of the RDF supply chain to maximize impact.

Keywords: life cycle assessment; cement production; refuse-derived fuel; alternative fuels; environmental impacts; uncertainty analysis

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1. Introduction

Cement production is one of the most energy- and carbon-intensive industrial processes, responsible for roughly 8% of global CO_2 emissions [1,2]. This large carbon footprint arises from the calcination of limestone into clinker and the combustion of fossil fuels, often coal or petcoke, to heat cement kilns [3,4]. According to the International Energy Agency (IEA), the direct CO_2 emissions intensity from cement production remained relatively stable from 2018 to 2022, increasing in 2022, and stayed within the range of 0.6–0.9 t CO_2 per ton of cement [5–10]. Additionally, an overview study reaffirmed that raw material processing in cement continues to emit approximately 0.8–1.0 tons of CO_2 per ton of cement, particularly in facilities without carbon capture and with high clinker ratios [11]. Beyond climate impacts, cement production generates significant air pollution, including nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particulate matter, and consumes substantial raw materials and energy [6,12,13]. These environmental impacts are of growing concern as

developing regions increase cement production to meet their infrastructure needs. Africa, in particular, has experienced rapid growth in cement demand over the past two decades, with many new plants built across sub-Saharan countries [14,15].

Most African cement plants rely on imported coal or heavy fuel oil for kiln energy, and few have yet adopted low-carbon technologies [7,16,17]. One viable strategy for reducing fossil fuel use is the adoption of alternative fuels, such as refuse-derived fuel (RDF) from municipal solid waste (MSW), which is processed to achieve a high calorific value and low moisture content, and is commonly used in cement kilns [18,19]. RDF is a fuel produced from non-recyclable waste materials, typically comprising combustibles such as plastics, paper, textiles, and wood, which are processed to achieve a high calorific value and low moisture content [20]. Peer-reviewed studies report that RDF has a significantly higher heating value (28–30 MJ/kg) compared to raw MSW (19–23 MJ/kg), making it well-suited for thermal applications [21–25]. Although widely adopted in countries like Germany, Italy, the US, and the UK, RDF utilization is also gaining traction in low- and middle-income countries, such as India and sub-Saharan Africa (SSA) [26,27].

In Europe alone, RDF supplied approximately 12 million tons to cement and waste-to-energy plants in 2015, achieving a 30–60% reduction in fossil fuel use in many facilities [28–30]. Moreover, RDF can be further converted into fuels such as oil and gas through pyrolysis and gasification [26]. Between 2012 and 2016, the annual waste generation in sub-Saharan Africa (SSA) increased from 81 million tons to 174 million tons [27]. Despite this rapid growth, MSW management remains a critical challenge across the region. At the same time, African municipalities face mounting solid waste challenges, with millions of tons of waste produced annually and up to 90% of it ending up in landfills [20,31]. In 2018, the MSW collection in SSA coverage was estimated at 44% [27]. The intersection of a carbon-intensive industry and this growing waste management crisis presents a strategic opportunity for utilizing RDF in cement kilns. Studies estimate that the annual RDF production of 12–57 kilotons (kt) from just two cities could offset 10–30% of current industrial coal use, potentially avoiding up to 180 kts of CO_2 equivalent (CO_2 eq) emissions and yielding net annual cost savings of approximately USD 8.7 million [18].

RDF can reduce fossil fuel consumption and divert waste from landfills when used to replace a portion of coal or petcoke in cement kilns. Studies have shown that co-firing RDF in cement kilns can reduce greenhouse gas (GHG) emissions by up to 40% compared to coal, as well as certain pollutants [32–36]. For example, in Morocco, substituting 15% of petcoke's energy with RDF reduced kiln stack emissions [20]. A case study presents a suspension preheater cement plant in India that successfully achieved a 25% thermal substitution rate through the co-firing of RDF in the main burner [37]. In addition to environmental benefits, RDF offers economic advantages. A Moroccan plant reported savings of approximately USD 389 per hour by co-processing RDF [20], making RDF an attractive alternative fuel in the cement production process. The environmental impacts of RDF co-firing vary based on factors such as waste composition, substitution rate, and the effectiveness of emission control systems. The biogenic fraction of RDF, such as food or yard waste, contributes to net CO_2 emissions, as this portion is considered climate-neutral [38].

This study assesses the environmental impact of replacing coal with RDF in Portland cement production, considering a cradle-to-gate boundary. Controlled paired scenarios were first presented to isolate the effect of fuel substitution, using a common electricity mix and identical process parameters. Subsequently, country-specific contexts were reported, utilizing native electricity grids for two African plants (South Africa and Ethiopia). The objectives are as follows:

1. To quantify the environmental impact of substituting 20% of kiln heat with RDF relative to 100% coal.

2. To illustrate how plant context, e.g., electricity grid mix, changes absolute results without altering the direction of the fuel effect.

By emphasizing recent data and utilizing region-specific parameters from the Ecoinvent v3.7.1 datasets for Africa, this study provides a timely evaluation relevant for policymakers and industry stakeholders.

While global studies highlight the potential of refuse-derived fuel (RDF) to reduce emissions and support waste valorization, empirical life cycle data under African operational conditions remain limited. Most existing assessments are located in high-income regions, where waste treatment infrastructure, electricity grids, and regulatory frameworks differ markedly from those in sub-Saharan Africa. Furthermore, few comparative studies apply harmonized modeling across countries to isolate the fuel substitution effect under consistent methodological boundaries. As cement demand continues to rise in Africa, understanding the dual role of RDF in industrial decarbonization and municipal waste management becomes increasingly important. This study addresses the gap by conducting a paired cradle-to-gate LCA of RDF co-processing against 100% coal combustion in cement kilns, using representative data from South Africa and Ethiopia. The objective is to generate regionally relevant insights into the environmental and economic performance of RDF as an alternative fuel within African cement production systems. Additionally, this work extends beyond environmental impact by integrating country-specific policy instruments, such as carbon taxes and landfill credits, into a cost-effectiveness analysis. This policy-linked economic–environmental evaluation is not commonly addressed in existing RDF-LCA literature and offers regionally grounded insights to support practical decision-making in the African cement sector.

2. Literature Review

In contrast, RDF derived from fossil-based materials, such as plastics, offers limited GHG benefits. Additionally, the use of heterogeneous waste streams may introduce contaminants, including chlorine and heavy metals, into the kiln system. This highlights the importance of implementing rigorous pollution control measures and maintaining continuous emissions monitoring to ensure compliance with environmental standards [39]. LCA is a systematic method for evaluating the environmental impacts associated with all stages of a product's life cycle, from raw material extraction and production through to use, disposal, or recycling. In the context of cement production, LCA is used to quantify emissions, energy use, and resource consumption across various processes, including raw material preparation, clinker production, fuel combustion, and waste handling. It provides a comprehensive framework to quantify these trade-offs and benefits. Numerous LCA studies on cement have been conducted globally, examining strategies such as alternative fuels, clinker substitution, and carbon capture [7,14,15,38–41].

Çankaya and Pekey [42] conducted a comparative LCA of clinker production in Turkey using traditional fossil fuels and alternative fuels such as tire-derived fuel and dried sludge. The results showed that switching to alternative fuels reduced GHG emissions by approximately 16% compared to traditional fuel use. Çankaya and Pekey [43] expanded on their earlier work in 2018, assessing sustainability scenarios in Turkish cement production by comparing different fuel and raw material substitutions (at a 3% substitution rate) across multiple cement types (CEM I–V). Incorporating RDF and biomass reduced climate change impacts by 1.4%, human health impacts by 27%, ecosystem quality impacts by 10%, and resource depletion by 11%, with the lowest impacts in CEM IV (pozzolanic cement) and CEM II (blended cement). Moretti and Caro [44] employed an LCA to evaluate Italian cement production. The results revealed significant reductions in environmental impact through increased use of fly ash and blast furnace slag as clinker substitutes. The

substitution of 30% clinker with industrial by-products resulted in a 25–35% reduction in CO_2 emissions.

Additionally, this critical analysis revealed that substituting 10–15% of thermal energy with alternative fuels (RDF) resulted in reduced CO_2 emissions in Italian plants. However, it emphasized methodological inconsistencies in allocation approaches for accurate impact quantification, particularly for co-processing. Georgiopoulou and Lyberatos [45] conducted an LCA to evaluate the environmental performance of using alternative fuels, specifically RDF and biological sludge, in cement kilns compared to 100% petroleum coke. Their study demonstrated that substituting 30–40% of traditional fuels with RDF and other waste-derived fuels led to a 22–30% reduction in global warming potential (GWP), underscoring the environmental benefits of fuel switching in the cement production process.

Stafford, et al. [46] evaluated the LCA of Portland cement production in Southern Europe by substituting clinker with supplementary cementitious materials (SCMs) like fly ash or slag to reduce clinker content in cement. The results showed that the clinker production phase accounted for more than 85% of total emissions. Replacing 20% of clinker with limestone or pozzolanic materials could produce a 15–20% reduction in CO_2 emissions. Additionally, the blended cement, such as CEM II/V, outperformed CEM I across all environmental impact categories. Stafford, et al. [47] applied LCA to analyze environmental impacts and opportunities for improvement, focusing on the Brazilian cement industry. Partial clinker substitution with industrial residues, up to 40%, showed potential for a 30–40% reduction in emissions, particularly in the category related to global warming. They used an alternative fuel, and specific reduction percentages were not quantified. They found that transportation and fuel production contributed significantly to total impacts, alongside clinker production. However, they emphasized that logistics optimization and localized sourcing were also critical, typically resulting in 10–20% reductions in similar contexts, alongside material and fuel substitution.

Salaripoor, et al. [38] evaluated the environmental advantages of RDF over fossil fuels in cement production, demonstrating its potential to reduce carbon emissions and improve sustainability using LCA. They advocate for RDF as a viable low-carbon fuel option for the cement sector. Substituting 30% of fossil fuels with RDF achieved a 20–25% reduction in CO_2 eq emissions, confirming RDF as a key strategy for decarbonizing cement production. Panahandeh, et al. [39] conducted an LCA on clinker production using RDF derived from MSW in Tehran, showing a reduction in fossil fuel use and emissions. Co-firing RDF in a Tehran preheater kiln reduced the acidification potential by 2.14–11.5% and achieved GWP reductions in the range of 0–1.3% when RDF supplied 5–30% of the energy alongside natural gas, although NO_x emissions may increase without proper control. The results highlight the potential for integrating waste management with cement production for environmental benefits. These studies enable comparison of different scenarios, e.g., coal and RDF based on standardized impact categories like GWP, acidification, and human toxicity.

In the context of Africa, there is a relative lack of LCA research focused on African cement operations using alternative fuels. Beressa and Vijaya Saradhi [7] utilized LCA to assess GHG emissions, energy usage intensity, and resource exploitation at Mugher Cement Factory, Ethiopia, revealing significant environmental impacts associated with fossil fuel use. Substituting 50% of imported coal with coffee husks at Mugher Cement Factory resulted in a 14% reduction in GHG emissions, a 1.2% improvement in thermal efficiency, and a 36% reduction in coal costs. The authors concluded that substituting part of the fuel mix with alternatives could improve the sustainability of the plant. While such studies highlight the general importance of fuel choice on cement's footprint, Akintayo, et al. [15] assessed Portland cement production in South Africa using an LCA at midpoint impact categories, identifying clinker production as the major emission hotspot. No specific

substitution-driven emission reductions are quantified; the study primarily benchmarks environmental hotspots. For example, kiln fuel combustion dominates climate impacts, without testing alternative scenarios. The study supports process optimization and the use of alternative fuels to mitigate the environmental impacts.

Ige, et al. [48] employed an integrated LCA and system dynamics model to predict the long-term environmental impact and future dynamics of cement production in South Africa. The LCA focuses on assessing the emissions of primary pollutants, such as CO_2, nitrogen oxides (NO_x), and sulfur dioxide (SO_2), and their effects on GWP, human health, and other environmental factors. The study emphasizes the need for sustainable practices, suggesting policy changes like eco-blended cement production and carbon taxes to mitigate emissions. This innovative approach aims to guide future cement production while minimizing environmental impact.

To address potential emissions beyond GHGs, several studies have examined criteria and hazardous pollutants during RDF co-processing in cement kilns. For SO_2, case studies and reviews indicate that sulfur in RDF can contribute to formation. Yet, the kiln's alkaline environment and appropriate firing control generally maintain SO_2 within regulatory ranges comparable to coal baselines [34,37]. Regarding dioxins, experimental work in cement kilns co-processing hazardous wastes shows that emissions and distribution are highly sensitive to feed position and amount. Maintaining high temperatures and sufficient oxygen and avoiding conditions that promote de novo synthesis are essential for minimizing PCDD/F formation [49]. For trace metals, reviews and plant case analyses report that most metals are immobilized in clinker or captured in kiln dust, with compliance relying on stringent RDF specifications, sorting to limit hazardous fractions, and stable operation of the calciner and main burner. Attention to volatile metals remains important for minimizing stack releases [33,34,37].

3. Methodology

This study performs a cradle-to-gate comparative LCA of cement production using traditional fossil fuels (100% coal) versus partial substitution with RDF (20% RDF by thermal input). The analysis focuses on two representative cement plants in South Africa and Ethiopia, capturing regional differences in electricity grid mixes, fuel logistics, and RDF potential. This study follows the International Organization for Standardization (ISO) 14040/44 framework for LCA [50,51], structured across the four standard phases: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) impact assessment, and (4) interpretation.

3.1. Goal and Scope

The LCA framework applied in this study follows the principles outlined in ISO 14040/14044 [50,51] and is implemented in SimaPro 9.2.0.1, utilizing the Ecoinvent v3.7.1 cut-off database. The functional unit is defined as 1 kg of Portland cement at the factory gate. A cradle-to-gate system boundary includes five main life cycle stages: (i) raw material usage, (ii) clinker production, (iii) electricity usage, (iv) fuel usage, and (v) transportation. The use and end-of-life phases, such as concrete production and demolition, are excluded to focus on production-stage impacts, consistent with benchmarking practices in cement LCA.

While this study draws on data from two national contexts, South Africa and Ethiopia, it applies a harmonized LCA model to ensure methodological consistency and comparability. Coal-based production and 20% RDF substitution are developed for each country, using a consistent functional unit (1 kg of cement), a cradle-to-gate boundary, and a five-stage process structure. Site-specific parameters, such as national electricity grid mix, clinker factors, and fuel transportation distances, are incorporated to reflect regional conditions.

3.1.1. Clinker Production

This stage covers the kiln system (preheater, precalciner, rotary kiln), where raw meal is calcined and clinkered. It includes process emissions from limestone decarbonation and emissions from fuel combustion at the kiln, such as CO_2, NO_x, SO_2, and particulates, which are recorded as process emissions, as well as in-kiln control measures. It does not include fuel provision or delivery to the site. Clinker production is emphasized because it is typically the most significant contributor to CO_2 and thermal energy demand.

3.1.2. Raw-Material Stage

This stage involves quarrying and preparing limestone, clay, and minor additives to produce raw meal, which includes drilling, blasting, hauling, crushing, grinding, and homogenization, as well as ancillary quarry operations. It captures land use effects and energy for comminution. Calcination and material movements to the plant gate are excluded from this process.

3.1.3. Electricity Usage Stage

This stage accounts for the generation, transmission and purchased electricity used by plant operations for raw grinding, kiln drives, clinker cooling, cement grinding, conveyors, packing and utilities. Electricity is modeled using the applicable grid mix. For controlled comparisons, a common Ecoinvent dataset grid is applied, while country-specific grids are used for context analyses. Treating electricity as a distinct stage highlights its contribution to climate change and particulate-related indicators associated with power generation. South Africa's coal-based grid results in a higher emission factor [15,40], while Ethiopia's mix benefits from hydropower.

3.1.4. Fuel Usage Stage

This stage encompasses fuel provision and delivery, including coal or RDF supply to the firing point, as well as extraction/beneficiation or MSW-to-RDF preparation, fuel quality control, and any fuel-related air/water emissions specified by the data source. It includes MSW collection, sorting, shredding/drying/densification (where applicable), and RDF transport to the plant. A cut-off allocation is applied: waste enters as RDF with zero prior burden; only RDF processing and delivery are counted [20].

3.1.5. Transportation Stage

Transport activities encompass the movement of non-fuel materials to the plant, including quarry-to-plant limestone haul, coal delivery, RDF delivery, gypsum haul, and other logistics (mode, distance, and payload as specified). Distances reflect African practice, e.g., 200–500 km by rail/truck for coal regions and approximately 50 km by truck for RDF from urban facilities, where relevant to non-fuel materials. Emissions are primarily from diesel and are recorded separately due to their significant influence on photochemical ozone formation and particulate matter indicators [15]. Transport activity is modeled in tkm as (mass per functional unit) × (distance), following the Ecoinvent approach; one-way distances are used because return trips are embedded in the transport datasets.

To ensure clarity and reproducibility, scenario A and scenario B are defined a priori and consistently applied throughout the study. Scenario A (Baseline: Coal) represents the conventional cement production system, which utilizes 100% coal or coal/petcoke blends as its primary source of thermal energy, reflecting common practice in many African cement plants [7]. Scenario B (20% RDF + 80% coal co-processing) represents a partial substitution of coal with RDF, accounting for approximately 20% of the total thermal input on an energy basis. This substitution rate, based on lower heating value (LHV), aligns with

regional benchmarks, such as Egypt's 15% alternative fuel policy [52]. The RDF is assumed to originate from MSW after recyclable materials have been recovered, with an LHV of approximately 18.5 MJ/kg, consistent with Moroccan data [20].

This scenario involves the additional transportation of RDF from a municipal processing facility to the cement plant, along with the corresponding changes in emission profiles (CO_2, NO_x, SO_2, and PM_{10}). All subsequent references to results, inventories, and impact categories use these labels (Scenario A and Scenario B) for consistency. The two scenarios were modeled to evaluate the environmental impact of substituting conventional fossil fuels with RDF in the cement production process using SimaPro 9.2.0.1 software with the Ecoinvent v3.7.1 datasets. Both scenarios share identical system boundaries, cradle-to-gate, functional unit (1 kg of cement), and process configuration (dry rotary kiln process). The only variations between scenarios involve fuel type, combustion-related emissions, and associated transport distances.

3.2. Life Cycle Inventory Data

Life Cycle Inventory (LCI) data were primarily obtained from the Ecoinvent v3.7.1 database (cut-off system model), accessed via SimaPro 9.2.0.1 software. Wherever possible, data specific to Africa were utilized for cement production in Scenario A and Scenario B to enhance the accuracy of the assessment [53–56]. Table S1 presents the typical inputs, energy requirements, and emissions associated with producing one kg of cement in both scenarios, based on industry data and literature sources. The data represent approximate values for a modern dry-process cement plant that uses coal as fuel. Ecoinvent v3.7.1 provides a representative dataset aggregated for Scenario A from five cement plants, which cover 90% of production in South Africa [41]. Scenario B is documented in the literature, reflecting a different regional context [7]. The electricity grid in South Africa is approximately 90% coal, 5% renewables, and 5% other sources [52], whereas Ethiopia's grid is dominated by 95% hydropower and 5% other sources, with virtually no fossil fuel input [57]. Indirect and background contributions, such as emissions associated with electricity generation, are not listed in this table but are included in the impact assessment.

The Clinker production process was decomposed into a foreground process model to ensure transparent control of combustion emissions and fuel inputs. The default Ecoinvent dataset Clinker production at plant {GLO} includes both calcination and fuel combustion modules. To avoid double-counting, the internal combustion module was disabled by setting the thermal energy inputs to zero. The actual fuel use and emission data from both scenarios were linked to separate upstream processes. Hard coal, burned in an industrial furnace > 100 kW {GLO} and RDF, municipal, combusted in an industrial furnace {GLO}, were considered. Other inputs, such as raw materials, electricity, and transport, were retained or localized. This structure enables the replication of the foreground model and isolates the differences between fossil and RDF energy scenarios.

Regarding boundary exclusions (cradle-to-gate), the modeled system begins with raw material extraction and ends at the cement at the factory gate. The following processes/flows are excluded and do not contribute to the core results, as shown in Table 1. Where relevant, separate sensitivity scenarios are reported for the avoided landfill credit associated with RDF. These additions clarify scope decisions and reproducibility.

This dual-scenario design allows both inter-country comparison and within-country fuel substitution analysis, ensuring that differences in results can be attributed with greater confidence to the type of fuel rather than unrelated systemic variations. Global average data from Ecoinvent were used only when country-level alternatives were not available and were adjusted using plant-specific operational parameters where applicable. This approach

maintains the integrity of a comparative LCA while acknowledging and managing the limitations of data availability in emerging economies.

Table 1. Boundary exclusions and study limitations.

Excluded Item	Reason for Exclusion	Expected Influence	Mitigation/Notes
Concrete use & end-of-life	Outside cradle-to-gate scope	None on production results	Aligns with benchmarking LCAs; avoids mixing downstream variability
Capital goods & infrastructure	Long-lived; dilute per FU	Very low	Common practice; documented in scope
Quarry closure/rehab	Post-operation works	Very low	Not material at FU scale; declare in text
External Air-pollution control (APC) residue handling	Beyond the plant gate	Low–moderate, site-specific	In-plant APC electricity included; external disposal excluded
Minor auxiliaries (<1%)	De minimis screening	Very low	Mass/impact screen applied
Recyclables market effects	Indirect/rebound	Uncertain	Out of scope; acknowledge qualitatively
Off-site sanitary wastewater	Non-process	Negligible	Excluded; declare

3.3. Impact Assessment Method

Life cycle impact assessment (LCIA) was conducted using the midpoint characterization approach, focusing on a set of relevant impact categories. The ReCiPe 2016 Midpoint (H) method was used for impact assessment, and the Centrum voor Milieukunde Leiden (CML 2001) December 2015 version was employed for cross-checking the results of global warming, as both methods were implemented in SimaPro 9.2.0.1 software. Midpoint indicators translate emissions or resource uses into potential impacts, like climate change or acidification, before weighting or damage conversion. The categories analyzed in detail include:

- GWP_{100} years are measured in kg CO_2 eq, assessing contributions to climate change from greenhouse gases (CO_2, CH_4, N_2O, etc.).
- Terrestrial Acidification is measured in kg SO_2 equivalents, reflecting emissions that lead to acid rain (e.g., SO_2, NO_x).
- Eutrophication (Freshwater and Marine) is measured in kg P or kg N equivalents for nutrients causing algal blooms in aquatic environments (e.g., NO_x, NH_3, phosphate).
- Photochemical Ozone Formation (Smog) is measured in kg non-methane volatile organic compounds (NMVOCs) or NO_x equivalents, indicating precursors to ground-level ozone that affect human health (NO_x, VOCs).
- Particulate Matter Formation is measured in kg $PM_{2.5}$ equivalents, capturing the human health impact of primary and secondary aerosols (e.g., dust, SO_x, NO_x forming particulates).
- Human Toxicity (carcinogenic and non-carcinogenic) is measured in kg 1,4-dichlorobenzene (1,4-DCB) equivalents, aggregating the potential harm of emitted pollutants (heavy metals, organics) to human health.
- Terrestrial and Freshwater Ecotoxicity is also measured in kg 1,4-DCB eq for impacts on ecosystems from toxic releases.

- Fossil Resource Scarcity (or Depletion) is measured in kilograms of oil equivalent or megajoules, indicating the consumption of non-renewable energy resources.
- Water Consumption is measured in m^3, although this was of lesser focus unless differences arose (RDF processing might use some water for dust control, but this is not very important in this context).
- Land Use, measured in area·year modified, is relevant for quarry land and landfilling activities. Although RDF use could indirectly affect landfill demand, avoided landfill credit was not included in the base case analysis.

These categories encompass the major environmental concerns associated with cement production, as identified in prior research [15,40]. Global warming, fossil resource depletion, and toxicity metrics were expected to show the most significant differences between coal and RDF scenarios based on initial analysis. Impact assessment was performed for each scenario. The model for Scenario A was first validated by comparing the LCA results to published reference values. For example, the model's result for GWP in the SA plant was 0.993 kg CO_2 eq/kg, matching the literature value [15,40]. For the Ethiopian plant, the result was 0.84 kg CO_2 eq/kg, which is close to the reported value of 0.841 kg [7]. Such validation builds confidence in the inventory and impact calculations. After calculating the impact results for each scenario, a contribution analysis was performed using SimaPro 9.2.0.1 software to determine the share of each process stage in the total environmental impacts. This approach enabled us to quantify the proportion of GWP, for instance, attributable to clinker production, electricity use, and other processes under each fuel scenario. The stage breakdown was organized into the five categories defined within the system boundary. As a validation step, the results were compared with the GWP contributions reported by Akintayo, et al. [15] for South African cement production. Their results indicated that clinker production accounted for approximately 76.3% of the total GWP, electricity use accounted for around 18%, and the remainder was from minor inputs. The model produced a comparable distribution for the coal-based scenario, supporting the validity of the underlying modeling assumptions. These comparisons are discussed further in the Discussion Section (Section 4).

3.4. Case Study Plant Selection

Scenario A represents a modern dry-process cement plant located in South Africa, utilizing a precalciner kiln system with an annual production capacity of approximately one million tons of cement. The plant primarily relies on coal as its fuel source. The Ecoinvent v3.7.1 dataset integrates primary data from five major South African cement plants, collectively representing approximately 90% of the country's cement production [40,56]. It represents an average South African cement plant during the period from 2015 to 2020 in terms of technological configuration and energy efficiency. The plant produces cement with a clinker factor of approximately 90%. It operates with a specific thermal energy consumption of roughly 3.6 MJ per ton of clinker and an electricity consumption from the grid of around 110 kWh per ton of cement. Emission control measures include the use of low-NO_x burners and fabric filters, which align with South African environmental regulations. Notably, at the time of data collection, the adoption of alternative fuels in South African cement kilns remained limited, although an RDF processing facility was established in 2016 [31]. As a result, Scenario A is effectively 100% fossil-based, making it a suitable reference point for comparative analysis.

Scenario B is modeled after a representative East African cement plant, using one of the biggest cement factories in Ethiopia, based on the availability of detailed LCA data [7]. The plant operates a dry-process system with a preheater kiln, boasting an annual production capacity of approximately 0.7 million tons of cement. Its energy mix primarily includes

imported coal, comprising roughly 64% high-grade anthracite and 24% domestic lignite (by energy content), along with minor quantities of diesel or heavy fuel oil used during startup operations [7]. Reported energy performance includes a specific thermal energy consumption of approximately 3.5 GJ/ton of clinker and an electrical consumption of about 96 kWh/ton of cement [7], which is very comparable to Scenario A. The significant difference between the two scenarios lies in the grid emission intensity and geographic context. Ethiopia's national grid is primarily hydropower-based, resulting in significantly lower emissions related to electricity production.

Additionally, the plant is located at a high altitude with limestone of a different quality. However, these factors have only a minor influence on most midpoint impact categories. Nonetheless, Scenario B serves as an illustrative example of differences in fuel policy. While the plant does not currently utilize alternative fuels, there is growing interest in integrating biomass sources and RDF in East African cement plants in the near future. These two scenarios enable us to evaluate the RDF scenario under different grid mixes and supply chain conditions. For instance, coal transportation for Scenario B involves longer distances, as it is imported by ship and truck from South Africa to Ethiopia, potentially increasing the contribution of the transport stage compared to Scenario A.

3.5. RDF Definition and Quality Control

RDF in this study is derived from MSW after the removal of recyclables (metals, glass, and PET) and fines, then shredded, screened, and homogenized to meet the specifications of a cement kiln. The modeling of RDF quality and transport assumptions was developed with close reference to regionally representative data and operational practice in African cement plants. To ensure reproducibility and methodological transparency, RDF characteristics were explicitly parameterized based on reported values from pilot projects in Morocco, Tunisia, and East Africa. These parameters include lower heating value (LHV), biogenic content, moisture content, ash fraction, and chlorine and nitrogen levels (Table S2). The base case applies a biogenic carbon share of 50%, an LHV of 18.5 MJ/kg, and 10% moisture values, aligned with RDF derived from municipal solid waste after removal of recyclables, and kiln Quality Assurance/Quality Control guidance. Biogenicity directly influences the climate accounting framework and is treated in accordance with the Intergovernmental Panel on Climate Change (IPCC) guidance as carbon-neutral for direct emissions accounting. Sensitivity analyses, however, vary this fraction from 30 to 60% to test robustness.

Transport modeling assumptions are structured by material type, mode, and distance. RDF is assumed to be delivered by truck from a nearby urban waste processing facility within a 50 km radius, reflecting proximity constraints in RDF logistics. In contrast, coal is typically transported over 200–500 km by rail or truck, based on sourcing patterns in South Africa and Ethiopia. All transport emissions are calculated in ton-km using Ecoinvent v3.7.1 transport modules, with one-way trip modeling and embedded return flows. The contribution of transport to impact categories such as photochemical ozone formation and particulate matter is evaluated stage-wise.

This structured modeling approach enables attribution of environmental impacts to specific lifecycle stages and fuel characteristics. Where assumptions introduce uncertainty, they are explicitly tested in sensitivity scenarios described in Section 3.8.

3.6. RDF Specification & Justification

Scenario B assumes that plants have access to RDF derived from municipal solid waste (MSW), reflecting emerging waste-to-energy trends across Africa. Although the case studies are based on the conditions in Scenarios A and B, the results are broadly applicable to other African countries aiming to adopt RDF within the cement sector. To represent

cement-grade RDF suitable for African plants, a baseline specification was adopted based on regional literature and plant reports from North, West, and East Africa, as well as the Middle East and North Africa (MENA), along with Ecoinvent documentation for RDF used in co-processing, as shown in Table S2. To isolate the effect of fuel substitution from site context, the paired counterfactuals for each plant were considered with identical non-fuel parameters. A common grid-normalized variant was also performed using the same electricity mix for both plants to ensure that differences between coal and RDF scenarios reflect fuel substitution rather than variations in electricity composition. The RDF preparation involved mechanical pre-processing of source-separated municipal residuals, including screening, shredding, magnetic/eddy current sorting, and baling, which do not produce process wastewater. Only inert rejects (10–15 wt%) are diverted to landfill; the burdens of these non-combustible fractions are excluded from the cradle-to-gate boundary as they belong to municipal waste-management systems.

RDF substitution level: The base case applies a 20% RDF (thermal) rate. This level reflects a feasible operating point for the studied kiln types without major retrofit, consistent with (i) burner and feeding capacity, (ii) flame stability and clinker quality constraints (LSF/SRF, free-lime), (iii) control of alkali–chloride cycles and bypass dust, (iv) emissions compliance for NO_x, SO_2, HCl, and dust, and (v) continuous RDF supply quality (LHV $\approx$ 18.5 MJ/kg; ~10% moisture; Cl < 0.5%). Plants commonly adopt 10–30% during early co-firing programs, before increasing to higher levels once fuel preparation and process control are optimized. Therefore, a 20% substitution rate was used to isolate a realistic and reproducible effect while minimizing confounding operational variables.

The 20% RDF thermal substitution rate used in Scenario B reflects a technically feasible rate based on practical operating conditions commonly reported in African and MENA region cement kilns during the initial or intermediate stages of co-processing adoption, which range from 10% to 25% [20,52], aligning with guidelines from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) [58] and industry case studies from Titan Alexandria Portland Cement Company [59–61]. Although substitution rates above 50% are feasible in European plants with advanced feed systems and bypass dust controls [62], this level allows stable kiln operation without requiring significant hardware modifications, while providing meaningful environmental performance signals. Sensitivity to higher substitution rates, exceeding 30%, should be investigated in future work as RDF supply chains and kiln control systems mature.

3.7. Paired Scenario Design and Grid-Normalized Controls

For each plant, two paired scenarios were modeled: Coal (100%) and RDF (20% + Coal-80%). Within each pair, non-fuel parameters were identical: functional unit, clinker content, heat and power intensities, transport distances, and process settings. The electricity mix was held constant within the pair to prevent electricity composition from influencing the Coal and RDF delta. To further isolate the fuel substitution effect from geography, both pairs were repeated using (i) a generic Ecoinvent grid and (ii) each national grid applied to both scenarios. This yielded a grid-normalized counterfactual where differences between Coal and RDF reflected the fuel change rather than regional electricity composition. Stage-wise attribution followed the established five-stage structure. Additionally, a simple additive decomposition of the change between the Coal and RDF scenarios by stage is provided in the Supplement File.

3.8. Sensitivity Scenario: RDF Credit for Avoided Landfill Methane

To complement the cradle-to-gate results, a sensitivity analysis was conducted attributing avoided landfill methane emissions to RDF, using the IPCC First-Order Decay

(IPCC-FOD) method with a 100-year horizon to estimate methane generation from landfilled waste. RDF is produced from MSW with a 50% biogenic content, which is used at a 20% thermal share, corresponding to 0.04 kg of RDF per 1 kg of cement. IPCC default parameters for landfill gas generation are applied for DOC, DOC_F, κ, methane fraction F, methane correction factor MCF, oxidation (OX), and capture rate (R). The credit is first calculated per ton of RDF and then scaled per 1 kg of cement. A central case is reported (R = 50%, OX = 0.1), along with bounding scenarios: low credit (R = 75%, OX = 0.1) and high credit (R = 0%, OX = 0.0). The complete set of input parameters is provided in Supplementary Table S3a.

$$CH_{4/ton}RDF = MCF \times DOC \times DOC_F \times F \times \left(\frac{16}{12}\right) \quad (1)$$

where

MCF = methane correction factor;
DOC = Degradable organic carbon in MSW;
DOC_F = Fraction of DOC that decomposes;
F = methane fraction.

Functional unit application: The analysis is applied to the production of 1 kg of cement, incorporating a 20% RDF substitution by thermal input in the kiln. Assuming the clinker kiln energy demand is 3.5 MJ per kg cement, typical for modern kilns, a 20% thermal substitution means 0.7 MJ of RDF energy per kg cement. If RDF's calorific value is about 15 MJ/kg, this corresponds to roughly 0.05 kg of RDF used per 1 kg of cement [59]. The GWP_{100} of cement production will be compared with and without the inclusion of this credit.

3.9. Quantifying Economic–Environmental Benefits of RDF Substitution

To illustrate the potential economic–environmental synergy of RDF substitution in cement production, a cost-effectiveness (CE) metric (USD per t CO_2 eq avoided) was calculated along with a net financial impact ($\Delta\prod$) per ton of cement. This integrates South Africa's carbon tax policy, fuel cost differences, and an optional landfill fee/credit when the avoided-burden scenario is presented as a sensitivity.

3.9.1. Cost-Effectiveness of Abatement

This metric measures the net cost or savings associated with reducing each ton of CO_2. This framework enables site-specific inputs to be applied transparently, guiding phased RDF adoption that is both environmentally sound and financially viable.

$$CE = \frac{\Delta C_{fuel} + \Delta C_{RDF} + \Delta C_{ops} - B_{carbon} - B_{landfill}}{\Delta tCO_2} \quad (2)$$

where

$\Delta C_{fuel} = C_{coal,ref} - C_{coal,RDF}$ (coal cost saved);
$\Delta C_{RDF} = C_{RDF,net}$(RDF price minus any gate-fee revenue);
ΔC_{ops} = incremental O&M (e.g., handling);
$B_{carbon} = P_{CO_2} \times \Delta tCO_2$ with P_{CO_2} the applicable carbon price/tax;
$B_{landfill}$ optional credit from avoided landfill fees/emissions;
ΔtCO_2 from LCA (0.033 t CO_2 eq per t cement at 20% RDF).

3.9.2. Net Financial Impact

This indicator captures the overall change in production cost per unit of cement when using RDF.

$$\Delta\prod = \Delta C_{fuel} + \Delta C_{RDF} + \Delta C_{ops} - B_{carbon} - B_{landfill} \quad (3)$$

where

$\Delta \prod$ = Net financial impact/t cement;

ΔC_{fuel}(Coal cost saved) = coal price × coal avoided;

ΔC_{RDF}(RDF cost) = RDF price × RDF energy;

ΔC_{ops}(Incremental O&M) = 0.50 USD/t cement;

B_{carbon}: (Carbon credit) = Carbon price × ΔtCO_2;

ΔtCO_2 from LCA (0.033 t CO_2 eq per t cement at 20% RDF);

$B_{landfill}$: Landfill credit (sensitivity) = (Landfill credit × RDF mass).

The South African parameter values, presented as ranges in Table S6a, are applied, enabling reproduction with country-specific numbers, such as the South African carbon tax regime and municipal landfill tariffs (Carbon Tax Act, No. 15 of 2019). Applying the 2025 carbon-price level of ZAR 236 t^{-1} CO_2 (effective 1 January 2025), the avoided emissions of approximately 0.8 t CO_2 eq per kg RDF translate to a carbon-cost saving of ZAR 0.19 t^{-1} RDF [63]. Cost-effectiveness or Abatement cost is defined as the net cost change divided by avoided CO_2 (in \$/tCO_2) [64].

4. Results and Discussions

The LCI results for the traditional fuel scenario (100% coal) confirm that cement production is a resource- and emission-intensive process. As shown in Table S1, producing 1 kg of Portland cement requires roughly 1.5 kg of raw materials (mostly limestone) and about 3.3–3.6 MJ of thermal energy (from coal), plus 0.12 kWh of electricity. These inputs result in nearly 1 kg of CO_2 emissions per kg of cement, along with smaller quantities of other pollutants. In the modeled Scenario A, the cradle-to-gate GWP is 0.993 kg CO_2 eq per kg of cement, which aligns with reported values for Portland cement production in South Africa [14,15]. It is higher than the 0.84 kg CO_2/kg reported for partial production in Scenario B, which includes clinker substitution [7]. This CO_2 emission comprises both process CO_2 from limestone calcination and combustion CO_2 from the fuel. In fact, the clinker production stage alone, excluding electricity and transportation, emits approximately 0.78 kg CO_2 per kg of cement, which accounts for about 78–80% of the total GWP. The remaining CO_2 comes indirectly from electricity generation and transportation, which is notably significant in the South African context due to its coal-heavy grid.

From a materials perspective, producing 1 kg of Portland cement typically requires 0.90 kg of clinker, along with 5% gypsum and 5% limestone filler (by mass of cement). To produce this clinker, approximately 1.35 kg of raw meal, primarily composed of limestone, is used. During calcination, $CaCO_3$ in limestone decomposes into CaO and CO_2, releasing approximately 0.45–0.50 kg of CO_2 per kg of cement, primarily from the limestone. This explains why the raw material consumption stage is so significant for resource depletion: effectively, 1.3 kg of non-renewable mineral (limestone) is consumed per 1 kg of cement, and this limestone is permanently transformed (much of it into CO_2 gas and the rest into clinker). Indeed, the results show that raw material extraction dominates the mineral resource scarcity impact indicator, accounting for 99.9% of that impact, which reflects the large mass of limestone removed and the energy required to mine and process it. In most other impact categories, however, the raw material stage contributes very little, mostly some dust and a small amount of CO_2 from blasting operations.

Energy-wise, the direct coal usage of 0.17 kg/kg of cement may seem small, but coal is highly carbon-intensive. That amount of coal contains roughly 0.12 kg of carbon, which, when burned, forms about 0.44 kg of CO_2, plus approximately 0.50 kg of CO_2 from the calcination of limestone and smaller contributions of 0.05 from electricity, totaling 0.99 kg of CO_2 [15]. This is consistent with the reported GWP value of 0.99 kg CO_2 per kg of cement in this study. The inventory indicates a coal energy intensity of approximately

3.3–3.6 MJ per kilogram of cement, which aligns with the kiln thermal energy demand of modern dry-process kilns, typically ranging from 3.2 to 3.8 MJ per kilogram of clinker. The electricity intensity in this study was approximately 0.11 kWh/kg of cement for Scenario A. For Scenario B, the value was slightly lower, at 0.096 kWh/kg, reflecting an efficient plant and a greener grid that may have encouraged less in-house grinding energy due to possibly easier-to-grind clinker or other operational differences. This electricity is used for crushing, grinding, conveying, and other plant operations that require raw materials. Although the electricity energy is smaller in quantity than the thermal energy, its impact can be considerable if the power grid is carbon-heavy. In Scenario A, electricity contributed 18% of the total GWP, given a grid emission factor of approximately 1 kg CO_2/kWh, because South Africa's grid is 90% coal-based. In Scenario B, the cleaner grid meant that electricity contributed only 5–6% of GWP, as the grid is dominated by hydropower.

Regarding other emissions, the inventory indicates approximately 0.00421 kg of NO_x, comprising NO and NO_2, emitted per kilogram of cement from the kiln, primarily due to fuel combustion at high temperatures. This corresponds to 2.5 kg NO_x per ton of clinker, which is within the typical ranges for preheater/precalciner kilns without specialized NO_x reduction systems. These NO_x emissions are crucial for downwind air quality, as they contribute to smog, ground-level ozone formation and acidification (through the formation of nitric acid). The results showed that the photochemical ozone formation potential is primarily driven by kiln NO_x emissions, with additional contributions from transportation and power plant emissions. For example, 0.00421 kg NO_x eq per kg cement in Scenario A is attributable to ground-level ozone precursor potential, mainly from the kiln. This impact category will be one to watch when introducing RDF, since different fuels can alter NO_x emission profiles.

SO_2 emissions in the inventory are on the order of 3–5 g/kg of cement, originating from sulfur in the coal and raw materials. In limestone-rich kilns, a portion of SO_2 gets scrubbed by the alkaline lime in the kiln, forming $CaSO_4$, so actual emissions depend on raw material chemistry and kiln management. Typical emission levels were assumed, contributing to local impacts associated with terrestrial acidification. Dust (particulate) emissions were approximately 1 g/kg of cement in the inventory, which is well below most regulatory limits, on the order of 30–50 mg per Nm^3 of flue gas, translating to only a few grams per ton of cement. Still, cumulatively, cement plants can be significant sources of dust if filters fail, and dust contributes to particulate matter impacts. The Ecoinvent dataset also includes trace emissions of heavy metals, for instance, Hg (0.02 mg/kg of cement) and small amounts of others, such as lead and chromium. However, these masses are tiny; they have a disproportionate influence on toxicity-related impact categories.

The two case-study scenarios were modeled: Scenario A (South Africa Plant) and Scenario B (Ethiopia Plant). The core process exhibited highly similar inventory profiles across both scenarios, enhancing confidence in the validity of the generalized inventory. The main differences were that Scenario A had higher electricity usage and thus indirect CO_2 emissions due to its coal-dominated grid, while Scenario B had slightly higher transportation emissions since coal had to be transported over long distances to that landlocked region. These differences did not significantly alter any midpoint impact category results; they would become more pertinent in endpoint (damage) assessments, such as human health impacts, where the higher pollution from coal power in South Africa might be more pronounced. For midpoint indicators, contextual differences are noted; however, the emphasis remains on identifying general trends.

When RDF is introduced as a co-fuel, partially replacing coal, the resulting inventory changes are modest at the examined 20% substitution rate. In Scenario B, the coal input per kg cement decreases by 0.03–0.04 kg and instead, 0.04 kg of dry RDF is used. The

total energy input to the kiln remains 3.3 MJ/kg, so clinker production energy demand is met equally in both scenarios. The notable inventory shifts include a decrease in fossil CO_2 emissions from the kiln fuel, as 20% of the fuel carbon is now of biogenic origin and typically not counted as fossil GHG. In turn, biogenic CO_2 emissions increase by roughly an equivalent amount, 0.02–0.03 kg biogenic CO_2/kg cement, released from the biomass fraction of RDF, such as paper, wood, and food waste components. The total CO_2 emitted from the kiln does not change significantly in absolute terms, but the accounting of biogenic versus fossil carbon does, which affects GWP as an indicator.

NO_x emissions in inventory increase slightly by 5% under Scenario B to 0.00442 kg/kg cement, approximately 4.4 g, up from 4.2 g. This suggests that RDF, depending on its nitrogen content from protein, food residues, textiles, and other sources, can produce more NO_x per unit of energy than coal. If, on the other hand, RDF is composed mainly of paper, plastics, and other low-nitrogen materials, the NO_x increase might not occur. An intermediate assumption was adopted wherein RDF possesses a moderate nitrogen content, leading to a slight increase in NO_x emissions. All other emissions, such as SO_2, dust, and metals, were maintained at roughly the same level or improved in Scenario B. Sulfur input from RDF is negligible compared to coal, as RDF generally has low sulfur, especially if it is primarily municipal waste-derived, so SO_2 emissions were expected to decrease. An estimated 10% reduction in SO_2 emissions was applied, corresponding to approximately 0.3–0.5 g less SO_2 per kg of cement, a minor absolute change but beneficial in lowering the acidification potential. No significant change was expected in the dust emissions. In fact, some kiln operators report that firing certain waste fuels can produce less ash than coal, depending on the ash content of the fuel. The assumed RDF composition included approximately 10% ash, comparable to or lower than that of many coals; therefore, no adjustments were made to dust emissions in the model.

In summary, at the inventory level, switching 20% of the fuel input to RDF resulted in lower fossil CO_2 emissions and lower SO_2, roughly the same total CO_2 if biogenic CO_2 is excluded from GWP, and a potential slight increase in NO_x. The magnitude of these shifts was not dramatic at a 20% substitution rate, which underlines the need to examine results across various impact categories to assess the cumulative environmental effects of the fuel switch.

4.1. Environmental Impact Comparison (Midpoint Results)

Following the LCIA, characterization results were obtained for each scenario across multiple midpoint impact categories. Table 2 below presents a subset of these results per 1 kg of cement produced, focusing on key categories where notable differences between Scenario A and Scenario B were observed.

Table 2. Selected midpoint impact results per 1 kg of cement for Scenario A and Scenario B.

Impact Category	Units	Scenario A	Scenario B	Change (%)
Global Warming Potential	kg CO_2 eq	0.993	0.960	−3.30%
Fossil Resource Scarcity	kg oil eq	0.139	0.125	−10%
Terrestrial Acidification	kg SO_2 eq	0.00394	0.00380	−3.50%
Freshwater Eutrophication	kg P eq	1.11×10^{-4}	1.05×10^{-4}	−5%
Photochemical Ozone Form.	kg NMVOC eq	0.00220	0.00225	+2%
Ozone Formation (health)	kg NO_x eq	0.00421	0.00442	+5%
Particulate Matter Form.	kg $PM_{2.5}$ eq	0.00110	0.00105	−4.50%
Human Toxicity (non-carc.)	kg 1,4-DCB eq	0.497	0.480	3.40%
Terrestrial Ecotoxicity	kg 1,4-DCB eq	1.09	1.07	−2%
Water Consumption	m^3	2.0×10^{-4}	2.1×10^{-4}	+5%

As shown in Table 2, the GWP for Scenario B is approximately 0.96 kg CO_2 eq/kg of cement, which is about a 3.3% reduction relative to 0.993 kg in Scenario A. While this difference is within the typical margin of uncertainty for LCA data, it does indicate a discernible downward trend in climate impact. The modest scale of the reduction is attributable to the limited substitution level, where only 20% of the thermal input in the kiln is replaced by RDF. Additionally, a significant fraction of RDF's carbon is biogenic; hence, it not counted as fossil CO_2 in standard GWP accounting. A higher RDF substitution rate, e.g., 50% of the total thermal input, would be expected to yield a more substantial GWP reduction, roughly on the order of 8–10% based on extrapolation from the results and evidence from the literature [39]. This aligns with the results of Panahandeh, et al. [39], who observed a decrease of around 5–11% in GWP when RDF supplied 30% of kiln energy in a scenario with a natural-gas baseline. It is important to put this in context: because natural gas is less carbon-intensive than coal, the relative climate benefit of substituting RDF in a coal-fired system, as in the study, could be even more pronounced per unit of energy replaced. For instance, assuming a typical coal emission factor of approximately 95 kg CO_2/GJ and an effective fossil emission factor of 50 kg CO_2/GJ for RDF, accounting for roughly 50% biogenic carbon content, a 20% thermal substitution of coal with RDF would reduce fuel-related CO_2 emissions by approximately 10%. When spread across the entire cement production emissions, this translates to a net GWP reduction of roughly 3–4%, which is consistent with the findings of the study's detailed LCA model.

Therefore, Scenario B offers a measurable but modest climate benefit. The absolute CO_2 reduction is constrained by the limited substitution ratio and the fact that the dominant source of CO_2, the limestone calcination in clinker production, remains unchanged. Achieving more substantial emissions abatement will require either higher RDF co-firing rates or integrating complementary strategies such as reducing the clinker factor, switching to alternative cements, or implementing carbon capture. Nonetheless, even a 3% reduction in GWP, equivalent to approximately 30 kg CO_2/t cement, can yield significant cumulative benefits at the industry scale, amounting to thousands of tons of CO_2 avoided annually for a single large cement plant.

The Fossil Resource Scarcity indicator shows a notable improvement of approximately 10% under Scenario B, decreasing from 0.139 to 0.125 kg oil eq/kg of cement. This result is expected, as using RDF directly reduces the consumption of fossil fuels (coal). The observed 10% reduction correlates with a 20% reduction in thermal energy substitution of coal, after accounting for the differences in energy content and the weighting of different fossil resources. It is worth noting that raw material use, such as limestone, etc., is identical in both scenarios, so the fossil resource depletion category is driven almost exclusively by the use of coal and, to a lesser extent, diesel and other fossil inputs for electricity/transport. By incorporating RDF, the plant achieves a roughly 10% reduction in non-renewable energy demand per unit of cement, even if there is a small increase in diesel use for waste collection and RDF processing; that contribution is negligible relative to the coal savings.

Beyond the direct environmental impact, this shift has strategic co-benefits: it reduces dependence on imported coal, potentially improving energy security and insulating the operation from coal price volatility. While the fossil resource scarcity category does not represent an immediate environmental impact per se, it serves as a sustainability metric indicating reduced drawdown of finite resources. In essence, RDF use in the kiln helps conserve fossil fuel reserves. Additionally, by utilizing waste as fuel, the cement industry contributes to a circular economy approach, converting residual waste into energy, which aligns with broader resource efficiency and waste reduction goals.

Terrestrial acidification potential shows a minor reduction of about 3.5% in Scenario B. Specifically, the modeled acidification impact drops from 3.94×10^{-3} to

3.80×10^{-3} kg SO_2 eq/kg cement under the RDF co-firing configuration. This improvement, though modest and likely within uncertainty ranges, suggests a slight environmental advantage from the fuel swap. In the model, the reduction in SO_2-related acidification emissions attributable to the lower sulfur content in RDF compared to coal more than offsets the slight increase in NO_x-related acidification emissions, recognizing that NO_x contributes to acidification through the formation of nitric acid in the atmosphere. The net result is a slight decrease in acidification potential. If RDF had a high chlorine or nitrogen content, it could potentially increase acidifying emissions through HCl or additional NO_x; however, the assumed RDF composition in this study was relatively clean, with low sulfur and chlorine content. Essentially, using RDF in place of high-sulfur fuels like coal tends to lower SO_2 emissions, which is beneficial for mitigating acidification. Empirical evidence supports this: for example, a study at a Moroccan cement plant co-firing RDF observed a measurable reduction in SO_2 emissions and no significant increase in NO_x after optimizing the combustion process [20]. This suggests that in regions where coal has moderate sulfur content, as is common in parts of Africa, RDF co-firing can be acid-neutral or slightly beneficial for acidification, especially if kiln operators carefully manage combustion conditions to prevent NO_x increases.

The eutrophication impact results, both for freshwater and marine, showed a very slight improvement of roughly 5% with the RDF scenario. For instance, the freshwater eutrophication potential decreased from 1.11×10^{-4} to 1.05×10^{-4} kg P eq/kg cement in Scenario A. This change is minimal in absolute terms, but it indicates a subtle shift in environmental impact. Eutrophication in cement production is primarily influenced by NO_x emissions, leading to nitrate deposition and potentially phosphate runoff from raw material mining. Given the assumption of a 5% increase in NO_x emissions for Scenario B, a slight increase in eutrophication potential might be expected.

The results indicate a net decrease, suggesting that upstream emissions from coal mining, such as nitrate or sulfate runoff, were sufficiently reduced through decreased coal usage to offset the additional NO_x emissions from the kiln. It is a sensitive balance; replacing some coal with RDF likely reduces some emissions in the coal supply chain that affect water quality. However, it is important to emphasize that this 5% change falls within the uncertainty range of the assessment and is not considered statistically robust. Moreover, the contribution of cement production to eutrophication is minimal compared to many other sectors, on the order of 10^{-4} kg P eq per kg of cement [15]. Consequently, even if the use of RDF led to a marginal increase or decrease, the overall eutrophication impact of cement is negligible in a broader context. In simpler terms, the fuel switch does not meaningfully change nutrient emissions to waterways in either direction.

The photochemical ozone formation potential is related to smog creation, often quantified in terms of NMVOC or NO_x eq., and showed virtually no change between the scenarios. In fact, Scenario B had a slightly higher impact of +2% in NMVOC eq, or +5% in NO_x eq for the human-health-related ozone indicator, as seen in Table 2. This outcome corresponds to the slight increase in NO_x emissions that was assumed. RDF could also contribute to VOC emissions if not fully combusted, for instance, from any plastics that are not completely burned. However, given the high-temperature environment of a cement kiln, combustion is typically highly complete; therefore, no significant increase in CO or unburned hydrocarbons is expected. The roughly 5% increase in ozone precursor potential is minor in absolute terms. Moreover, in practice, cement plants have methods to mitigate NO_x, such as using low-NO_x burners or injecting ammonia/urea in SNCR systems, and these measures would also apply under RDF co-firing to keep NO_x in check. Studies have noted that co-firing alternative fuels does not significantly increase emissions of CO or total hydrocarbons as long as the kiln operates under optimal conditions [39]. The analysis

assumed reasonable combustion control; therefore, potential impacts from incomplete combustion were not included. Overall, any marginal increase in photochemical ozone formation potential attributable to RDF-related NO_x emissions is considered manageable and likely insignificant under standard operational controls.

The particulate matter formation potential related to human health impacts of $PM_{2.5}/PM_{10}$ showed a modest improvement of about 4–5% in Scenario B. Numerically, it went from 1.1×10^{-3} to 1.05×10^{-3} kg $PM_{2.5}$ eq per kg cement. This reduction is primarily attributed to lower SO_2 emissions, as SO_2 can form secondary particulate sulfates in the atmosphere, and slightly reduced dust from coal mining and handling, resulting from the use of less coal. No increase in direct dust emissions from the kiln was assumed with RDF usage, and emissions from RDF processing were not significant within the LCA. Therefore, the RDF scenario benefits from avoiding some of the upstream particulate emissions associated with coal extraction, e.g., mining operations and haulage. Although a 4.5% decrease is slight, it suggests that co-firing RDF did not exacerbate particulate impacts and may have even provided a slight benefit. By partially reducing coal use, a corresponding decrease in particulate pollution associated with the coal life cycle is achieved. It is worth noting that if RDF requires extensive pre-processing, such as shredding, any dust from these operations would typically be controlled on-site at the RDF plant and would be a separate issue; in this case study, these were negligible. The bottom line is that Scenario B can achieve a similar or slightly lower particulate impact compared to coal-only, primarily due to cleaner combustion by-products, lower sulfur content and cleaner upstream processes.

The toxicity-related midpoint categories, namely human toxicity, non-carcinogenic and terrestrial ecotoxicity, also showed minor improvements in Scenario B. Human toxicity potential decreased by approximately 3.4% from 0.497 to 0.480 kg 1,4-DCB eq, and terrestrial ecotoxicity decreased by ~2%. These changes are modest and within uncertainty, but they align with the expectation that coal contains trace amounts of toxic heavy metals, such as mercury, arsenic, and lead, which contribute to these impact categories [15]. In Scenario A, for example, the human toxicity impact is primarily driven by emissions of heavy metals from coal combustion and coal mining. Substituting a portion of coal with RDF is presumed to reduce the introduction of certain metals, such as mercury, into the system, as municipal RDF typically contains lower mercury content than coal. RDF may contain other metals, e.g., zinc from paper inks or copper from wires. In the model, most metal emission factors were left unchanged for the 20% RDF scenario, implicitly assuming that metals introduced via RDF were approximately offset by those reduced from coal, leading to only a slight net benefit in terms of toxicity.

It is important to note that the RDF was assumed to be free of hazardous waste components, such as batteries or electronic waste containing heavy metals; a well-managed RDF supply is expected to exclude such materials. Thus, the slight decrease in toxicity potential suggests that partial coal replacement can reduce specific pollutant emissions, particularly mercury from coal, to some extent.

The only issue that should be discussed in this context is the potential emission of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), commonly referred to as dioxins and furans, when burning waste-derived fuels. The LCA did not explicitly include dioxin emissions. In cement kilns, the exceptionally high flame temperature (1450 °C) and long residence time can destroy most organic compounds. Plants that use RDF monitoring and control for dioxins often find levels still within regulatory limits. Under proper operation and steady kiln conditions, with no feeding of extremely chlorine-rich or inappropriate materials, co-firing RDF does not significantly increase dioxin/furan emissions. Scenario B was modeled under the assumption of best practices; therefore, no dioxin-related impacts were assigned. However, it is acknowledged that if the RDF feed quality is poor, e.g., high

PVC plastic or other chlorine sources, or unstable combustion conditions, PCDD/F formation may occur; however, this is outside the scope of the intended scenario, which assumes competent operation and RDF preparation. Literature generally finds that cement kilns, when well-managed, can co-incinerate waste fuels without exceeding dioxin emissions of concern, due to the kiln's effective destruction capability.

Regarding water consumption, the results showed essentially no significant difference between scenarios. Scenario A and B both required approximately 2×10^{-4} m^3 (0.0002 m^3) of water/kg of cement; this is process water use, not including, e.g., power plant cooling water, which might be indirectly accounted for in some impact methods separately. Scenario B was 5% higher, which in absolute terms is a minuscule 0.00001 m^3 difference, likely attributable to any water used in RDF processing (for instance, for dust suppression or in making RDF pellets). In effect, water use is not a key differentiator in this case. Cement production is not very water-intensive overall on a per-kg basis, and a 5% change on such a low base value is environmentally negligible.

To summarize the midpoint comparisons: Scenario B yields minor yet consistent improvements in most impact categories relative to the baseline. The most significant benefit is a reduction in fossil resource depletion of approximately 10%, primarily due to a decrease in coal usage. GWP is reduced by a few percent, 3%, acidification by a few percent, eutrophication by a few percent, and particulate formation by a few percent. Human toxicity and ecotoxicity show slight improvements of 2–3%. Photochemical ozone formation potential is characterized by a slight increase, with a 2–5% rise due to a slight increase in NO_x; however, as discussed, this is a manageable and minimal change. These results suggest that using RDF as 20% of kiln fuel can improve the environmental profile of cement production modestly without significant downsides. It is essentially a way to reduce fossil CO_2 and fossil resource use, and to a lesser extent, other pollutants, with only minimal trade-offs. It is noteworthy that the 20% substitution rate represents a relatively conservative estimate, as many European plants have achieved substantially higher rates. Studies project that achieving a 50% RDF substitution could proportionally enhance the associated environmental benefits. One study estimated a reduction of up to 15% in GWP at 50% replacement of alternative fuel [42]. However, in practice, higher substitution may introduce diminishing returns or operational challenges, such as the presence of chlorine and moisture at higher RDF rates. The results at 20% provide a baseline case that indicates a generally positive direction for all midpoint impacts.

4.2. Contribution of Process Stages to Impacts

To gain deeper insight into environmental hotspots in cement production, the contribution of each major life cycle stage to various impact categories was analyzed. The system was divided into five stages: raw material usage, clinker production, electricity usage, fuel usage and transportation. Figure 1 graphically illustrates these contributions for Scenarios A and B, respectively.

In Scenario A, results confirm that the clinker production stage dominates the majority of impact categories related to emissions. Approximately 76.3% of the GWP is attributed to clinker production itself, i.e., the on-site process emissions from calcination and the direct CO_2 from fuel combustion in the kiln, which is consistent with previous literature for coal-fired cement plants [15,40]. Clinker production is also the most significant contributor to particulate matter formation, 65% of that impact, due to kiln dust and emissions of NO_x/SO_2 that form secondary particulates and to photochemical ozone formation 75% of the smog formation potential, driven by the kiln's NO_x emissions. Essentially, the kiln is the single biggest polluting process in cement manufacturing, as expected.

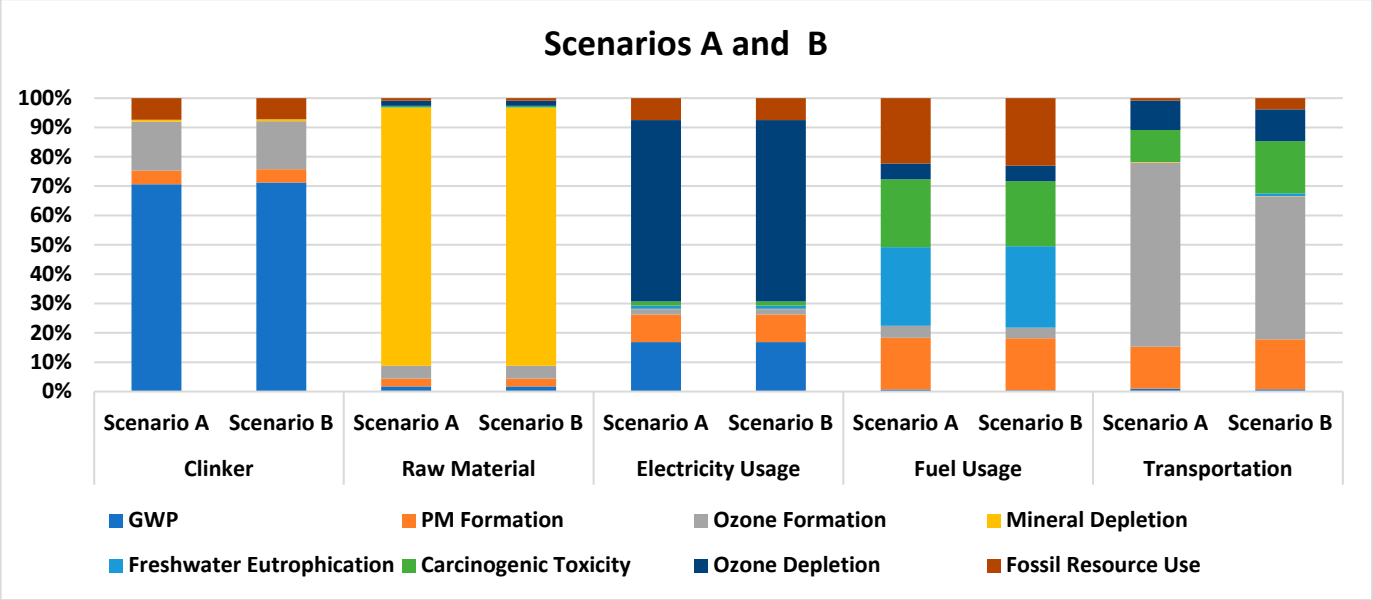

Figure 1. Contribution of Process Stages to Impact Categories.

The raw materials stage emerged as the primary contributor to the mineral resource depletion indicator, accounting for approximately 99.9% of that impact, which is logical because almost all non-renewable resource consumption involves the quarrying of limestone and other minerals in huge quantities. This stage had much smaller contributions to other categories. It does contribute a bit to indicators like ionizing radiation and terrestrial ecotoxicity, but that is mainly through the electricity and diesel used in mining; for example, if the grid has some nuclear power, that can show up in ionizing radiation potential, or if mining uses fuel that emits a bit of heavy metals, that can affect ecotoxicity [15]. However, in terms of air pollutants or climate impact, raw material extraction is minor, with some dust and CO_2 from mining equipment being the primary sources.

The fuel usage stage proved to be a significant contributor to several categories. Notably, this source was identified as the dominant contributor to freshwater eutrophication, accounting for 98.6% of the total impact. This suggests that activities in the coal life cycle, such as mining runoff or waste, which can contain nutrients or cause algal growth in water bodies, or NO_x from mining equipment contributing to nitrates, are the primary sources of eutrophication potential in the baseline. Similarly, the fuel stage was a substantial contributor to human toxicity (both carcinogenic and non-carcinogenic). For instance, the results of this study accounted for approximately 85% of the carcinogenic toxicity potential. This is likely due to heavy metal emissions, such as arsenic and nickel, associated with coal mining and combustion, which are known to be toxic to humans. So, even though these emissions may be small in mass, the coal life cycle contains some toxic elements that significantly influence the toxicity indicators.

The electricity stage was significant in several categories as well. In Scenario A, approximately 18% of the GWP is indirect CO_2 from electricity use, as the South African grid is primarily coal-fired [15].

In the model, the reduction in SO_2-related acidification emissions attributable to the lower sulfur content in RDF compared to coal more than offset the slight increase in NO_x-related acidification emissions, recognizing that NO_x contributes to acidification through the formation of nitric acid in the atmosphere. Electricity usage accounted for over 60% of the ozone depletion potential in the model. This outcome is partially an artifact of the impact assessment method, as it reflects upstream factors associated with the supporting grid infrastructure rather than direct cement plant operations. The transportation stage had

relatively minor contributions in most categories (<10%). One area where it was slightly higher was photochemical ozone and particulate formation, accounting for around 10–15% the impacts in Scenario A, reflecting emissions from diesel trucks/trains transporting coal and cement. For instance, in Scenario A, coal may be transported by rail or truck from the mine to the plant, resulting in some NO_x and PM emissions. These transport contributions are noticeable but not dominant. Other studies have found similar results, although in some cases where distances are considerable, transport can play a more significant role. A Brazilian LCA case study, for example, noted that transportation had a substantial share of specific impacts when raw materials or fuels were hauled over long distances, while on-site emissions dominated other impacts [47]. Overall, for Scenario A, the hotspot is clearly the clinker production phase for GWP, air pollution, and other impacts, followed by significant contributions from the upstream fuel cycle for specific impacts, toxicity and eutrophication, while raw materials dominate resource depletion. Electricity and transport play secondary roles except in the categories mentioned.

In Scenario B, the relative contributions of stages shift mainly in those categories related to fuel combustion and supply. Clinker production remains the most significant contributor to most impact categories, as it still produces the majority of CO_2, NO_x, etc. As coal-related emissions are reduced, the clinker stage's share of GWP increases slightly in percentage terms from 76.3% to 78.5%, due to the overall decrease in total GWP, making clinker CO_2 a proportionally larger contributor. The raw material stage continues to contribute 99% of mineral resource depletion, remaining unchanged, since limestone use remains the same, and the share of electricity in factors such as GWP or ozone depletion remains approximately the same, as the electricity use and mix did not change between scenarios in this comparison.

The most noteworthy changes occur in the fuel usage stage contributions: The fuel usage stage contribution to freshwater eutrophication decreases from 98.6% to 94% when 20% of the coal is substituted with RDF. It is still very high, and coal mining still causes most of the impact, but slightly less so. This stage contributes to human toxicity (carcinogenic), reducing it from 85% to 75%. Again, coal processes still dominate that category, but to a lesser extent, with some coal removed. The clinker stage share of GWP increases from 76% to 78.5%, as noted, because upstream (fuel) CO_2 emissions are reduced, making the remaining process CO_2 emissions relatively more prominent. The electricity usage stage contributions remain essentially unchanged in absolute terms and are thus slightly higher in percentage terms for some categories, due to the total impact being marginally lower in Scenario B; however, these differences are marginal. The raw material stage remains 99% of mineral depletion in both scenarios, since that is unaffected by fuel choice. The transportation stage contribution was roughly unchanged in the model. It was assumed that the RDF transport requirements had a similar energy use to the coal transport they displaced. If RDF was sourced more locally than coal, the transportation impacts would be expected to decrease; however, that benefit did not materialize here due to the assumptions.

These shifts underscore that reducing coal usage by 20% proportionally reduces the impacts primarily associated with the coal supply chain. Upstream coal mining has been a significant contributor to these specific impacts. Hence, reducing coal use by one-fifth corresponds to a corresponding lowering of those contributions, although not dramatically, but perceptibly.

It is instructive to observe that the clinker process remains the dominant contributor to GWP and multiple pollutants in Scenario B. This indicates that, despite improvements achieved through RDF substitution, the core emissions, particularly from calcination CO_2, continue to originate from clinker production. This highlights a key insight: fuel substitution alone, at this rate, does not change the fact that clinker production is the primary

environmental hotspot. In Scenario B, approximately 0.78 kg of CO_2 is still emitted from clinker production per kg of cement, as the clinker volume remains unchanged. This accounts for 78% of the total GWP. Thus, deeper decarbonization will require addressing the clinker CO_2 through measures such as reducing the clinker factor or implementing carbon capture, in addition to using alternative fuels.

From the contribution analysis, the results also confirm that the impact of mineral resource scarcity is entirely dominated by limestone use in both scenarios, accounting for 99% of the raw materials stage, and this remains unchanged with RDF. Therefore, any strategy focused solely on fuel will not affect that particular impact; addressing it would mean using less clinker (more Supplementary Materials in cement) or finding ways to reuse quarry waste, among other measures.

The categories heavily influenced by coal's upstream impacts, such as eutrophication and human toxicity, are improved in Scenario B but still largely stem from the remaining coal usage. This suggests an additional benefit of using RDF: it indirectly reduces impacts in coal mining regions, which, in an African context, could mean less water pollution and soil contamination in areas where coal is mined. In a region like South Africa, where coal mining can lead to acid mine drainage and heavy metal contamination, reducing coal use helps mitigate these environmental pressures. Therefore, an African cement plant using RDF not only reduces its own stack emissions slightly, but also potentially contributes to less environmental degradation at the mine source.

Comparing the two specific cases in their native contexts, in Scenario A, the plant's high-carbon grid meant electricity had a larger share of impacts, 18% of GWP, significant fractions of smog and PM due to power plant emissions, than in Scenario B, where electricity was cleaner, with only 6% of GWP. These differences remain in their respective roles in Scenario B. This suggests that in a country like South Africa, efforts to decarbonize the grid by introducing renewables or improving efficiency could substantially reduce impacts, such as GWP, beyond what fuel switching alone achieves. Conversely, in Ethiopia's case, the grid is already low-carbon, so the priority there would be fuels and the clinker factor.

The contributions analysis clearly delineates the influence of each mitigation strategy. RDF primarily reduces impacts associated with the fuel usage stage, namely fossil CO_2 from combustion, fossil resource depletion, and selected pollutants from coal. However, it does not affect impacts linked to limestone consumption, mineral depletion, CO_2 from calcination, or electricity use, unless RDF implementation indirectly facilitates waste heat recovery for power generation, which was not assumed in this analysis. For a holistic improvement, a cement plant would ideally combine strategies: use RDF and other alternatives to reduce coal-related impacts, utilize SCMs to lower clinker production, thereby decreasing calcination CO_2 and limestone use, and improve energy efficiency or use renewable power to minimize electricity impacts. For instance, studies have shown that adding even 5% limestone filler to cement can cut GWP by ~5–7% (due to reducing clinker production) and using high volumes of SCMs like fly ash or slag can achieve far larger CO_2 reductions, in one case a 20–35% CO_2 reduction with 30% clinker replacement [15]. In the African context, increasing the use of local SCMs such as calcined clay or natural pozzolana alongside RDF use could potentially yield cumulative CO_2 reductions of 30% or more, without accounting for advanced measures like carbon capture. This multi-pronged approach is likely needed to meet climate targets.

In summary, the stage-by-stage contribution analysis confirms that clinker production is the dominant source of emissions and impacts in both scenarios, with raw material extraction dominating resource-related impacts and the coal fuel cycle significantly affecting specific pollution categories. Using RDF at 20% mitigates some of the coal-related impacts, shaving off a portion of those contributions, but does not alter the clinker-related

impacts. These findings emphasize that while RDF co-firing is a valuable step toward sustainability, addressing part of the problem, it should be combined with other strategies, such as reducing the clinker-to-cement ratio and utilizing cleaner power sources, for a more comprehensive environmental improvement in the cement industry.

4.3. Controlled Fuel-Substitution Impact (Grid-Normalized Counterfactuals)

The primary impact quantified here is the fuel substitution from coal to 20% RDF, demonstrated through paired within-plant comparisons and grid-normalized controls. Geographic differences, notably in electricity mix, are presented separately to contextualize implementation but are not conflated with the fuel impact. To quantify the causal effect of substituting coal with RDF, Figure 2 presents results for both plants using a common electricity dataset and identical non-fuel assumptions, with the only difference being the kiln fuel (100% coal and 20% RDF + 80% coal). RDF substitution reduces GWP by ~3% (0.993 to 0.960 kg CO_2 eq·kg^{-1}) and fossil resource use by 10% (0.139 to 0.125 kg oil eq·kg^{-1}). Directionally consistent improvements are observed for terrestrial acidification (3–4%), freshwater eutrophication (5%), and particulate matter formation (4–5%). Photochemical ozone shows a minor increase of approximately 2–5%, which is operationally manageable through the control of low NO_x burners. Human toxicity (non-cancer) and terrestrial ecotoxicity decrease slightly by 2–3%. Water consumption is essentially unchanged at this substitution level. Across both plants, the direction and magnitude of the changes in coal and RDF are similar under identical electricity settings, indicating that the observed effects are attributable to the fuel substitution itself. These controlled results directly address the study's objective by quantifying the fuel effect independently of national grid differences.

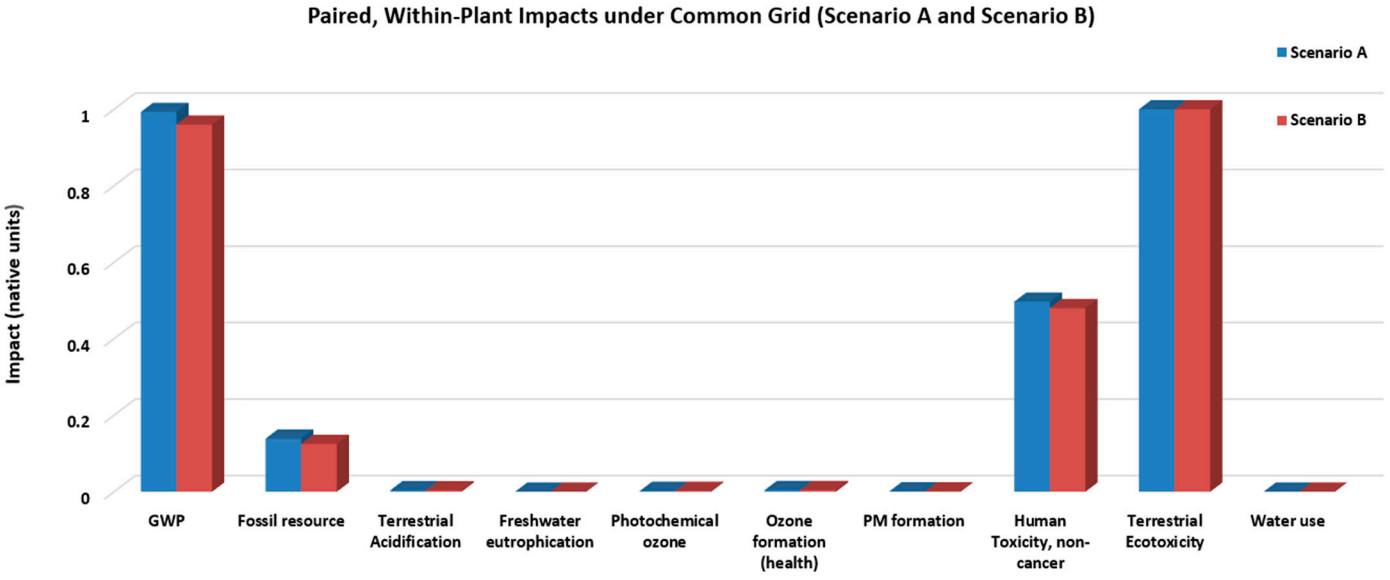

Figure 2. Common grid of Scenario A and Scenario B by midpoint category.

4.4. Plant-Specific Context (Native Grids and Settings)

The plant-specific native-grid results in Table S7 show how national electricity composition and logistics modulate absolute impacts without reversing the fuel signal. For Scenario A (a coal-intensive grid), electricity contributes a larger share of GWP than for Scenario B (a hydro-rich grid), which explains the lower absolute GWP for Scenario B under otherwise comparable assumptions. The Ethiopian cleaner grid lowers electricity-sensitive categories relative to South Africa, while kiln- and materials-driven categories remain similar. With RDF substitution, the direction of change observed in Section 4.3 is maintained for both plants, with lower fossil resource use, a modest GWP reduction (3%

GWP; 10% fossil resource) and slight shifts in air-quality-related indicators, confirming that the fuel signal is robust across different national contexts. This separation clarifies that fuel-only effects are analytically distinct from plant effects. Policy implications follow: where grid carbon intensity is high, complementary actions to decarbonize electricity, such as renewable sourcing or waste-heat power, can yield additional material gains; where grids are cleaner, the fuel strategy remains the most effective switch. These results, therefore, distinguish the environmental impact of fuel choice from differences attributable to grid composition and logistics. Figure 3 presents the native-grid results by country, comparing coal and RDF scenarios for South Africa and Ethiopia across multiple environmental impact categories per 1 kg of cement. The figure illustrates that RDF reduces global warming potential and fossil resource depletion, while also lowering acidification, eutrophication, human toxicity, and ecotoxicity. Slight increases are observed in ozone-related indicators and water consumption, though absolute values remain small.

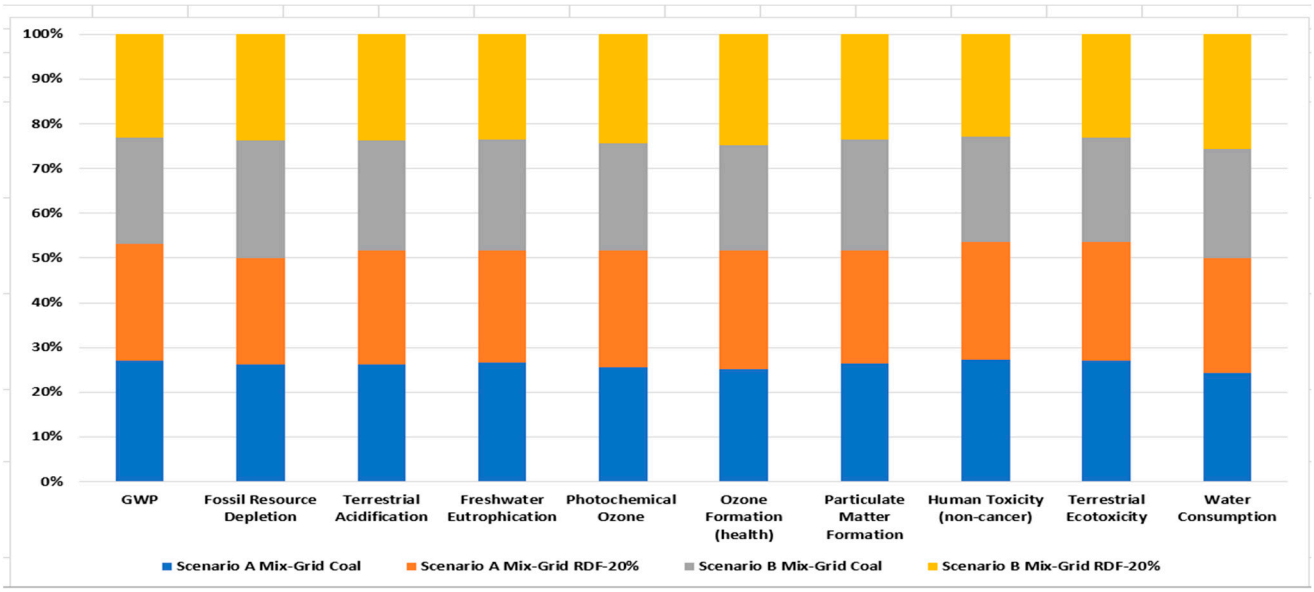

Figure 3. Native-Grid Results by Country.

The comparative analysis of Scenario A and Scenario B across South Africa and Ethiopia demonstrates consistent improvements in several environmental impact categories. RDF reduces GWP slightly in both countries (South Africa: 0.993 to 0.960; Ethiopia: 0.874 to 0.845), corresponding to a decrease of approximately 3.3%. Fossil resource depletion also declines from 0.139 to 0.125 in both cases, representing a reduction of about 10%. Indicators such as terrestrial acidification, freshwater eutrophication, particulate matter formation, human toxicity, and terrestrial ecotoxicity show modest decreases under RDF co-firing. Photochemical ozone formation and ozone-related health impacts increase slightly, while water consumption remains essentially unchanged, with only marginal variation observed. Overall, these results demonstrate that RDF integration yields measurable environmental benefits across multiple categories, with observed changes being consistent across both geographic contexts.

In both plants and scenarios, the clinker production stage is the principal hotspot for GWP (76–79%), fine particulate formation, and photochemical ozone formation. The raw materials stage dominates mineral resource scarcity (99%), unaffected by fuel choice. The fuel usage stage strongly influences eutrophication and toxicity; partial coal displacement with RDF lowers these contributions. The transportation stage is modest overall but can be

notable for ozone and particulate formation when distances are large; assumed distances here keep this effect small.

4.5. Uncertainty Analysis Results

Recognizing the uncertainties inherent in LCA data, especially in an African context with limited local data availability, is limited. A Monte Carlo uncertainty analysis was conducted using SimaPro 9.2.0.1 software, incorporating 1000 iterations with lognormal uncertainty factors sourced from Ecoinvent, and results are reported at a 95% confidence interval. The results are summarized in Table S4, which evaluates the robustness of the impact assessment results. For each midpoint impact category, such as GWP and acidification under Scenario A, uncertainty factors from the Ecoinvent database were applied as lognormal distributions, since this distribution avoids negative values and aligns with the multiplicative nature of environmental data. Geometric standard deviations from the database were used where available. Where the Ecoinvent database did not specify an uncertainty factor, a ±20% lognormal variation was assumed for the RDF calorific value, and a ±10% variation was applied to the coal heating value and emission factors. The analysis produced confidence intervals and standard deviations for each impact indicator, allowing us to determine whether differences between the coal and RDF scenarios were larger than the uncertainty ranges.

The analysis highlights both the strengths and limitations inherent in the midpoint LCA results. The study confirms that Scenario B shows largely uncertain changes across most midpoint indicators. Only GWP and fossil resource depletion exhibit differences between 3% and 10% that approach the width of the confidence intervals, providing medium confidence in their reduction. For GWP, the RDF scenario reduces emissions by 3.3%, but the 95% confidence interval for the coal scenario is ±5%, meaning the improvement is close to the limit of statistical significance. The fossil resource category shows a 10% reduction, matching the ±10% uncertainty assumption, which yields moderate confidence that RDF reduces non-renewable fuel consumption. Changes in acidification, eutrophication, particulate matter formation, and toxicity-related impacts are well within their respective uncertainty bands, suggesting that these reductions are not statistically robust. For example, freshwater eutrophication decreases by only 5%, which is half the assumed ±10% uncertainty; similarly, improvements in human toxicity and terrestrial ecotoxicity are far below their ±20% uncertainty. Photochemical ozone impacts slightly increase in the RDF scenario, but the differences are also uncertain. Water use shows negligible change, reflecting the low baseline water demand of cement production.

The inventory confirms that producing 1 kg of cement requires 1.5 kg of raw materials (mostly limestone), 3.3–3.6 MJ of kiln heat, and 0.12 kWh of electricity, yielding 0.99 kg of CO_2 eq in Scenario A and 0.96 kg of CO_2 eq in Scenario B (Table 2). Clinker production alone accounts for 0.78 kg CO_2 eq per kg of cement (78–80% of the GWP). Electricity's share of GWP is larger in Scenario A (18%) than in Scenario B (6%), consistent with grid composition. With RDF substitution (20%), coal input decreases by 0.03–0.04 kg per kg cement and is replaced by 0.04 kg RDF; fossil CO_2 drops, biogenic CO_2 rises accordingly, SO_2 falls (10%), and NO_x is modeled to increase modestly (5%). These shifts map directly onto the midpoint changes above.

In summary, the uncertainty analysis reveals that Scenario B offers modest environmental benefits; however, the magnitude of improvement is often comparable to the underlying data uncertainty. Although the results show reductions in GWP and clearer reductions in fossil resource use, higher RDF substitution ratios or additional decarbonization measures, such as clinker factor reduction or emission control technologies, would likely be required to achieve changes that are clearly distinguishable from baseline uncertainty. While this

traditional method improves methodological consistency, it likely underestimates the full climate benefit of RDF. Operational variables, such as kiln efficiency shifts, clinker factor changes, and ash behavior from RDF, were held constant for comparability; however, these factors may influence real-world outcomes. Despite these limitations, the study's regional case comparisons show that partial RDF co-firing serves multi-dimensional environmental benefits without significant exchange. The results are particularly relevant for African cement plants that are exploring alternative fuels in an evolving policy landscape, with carbon pricing mechanisms and waste valorization initiatives.

4.6. Sensitivity Result: Avoided Landfill Methane Credit

One aspect outside the strict cradle-to-gate scope is the avoided CH_4 emissions from diverting waste from landfills. If the RDF is sourced from municipal solid waste that would otherwise go to a landfill, using it as fuel can prevent the generation of landfill methane, a potent greenhouse gas. A sensitivity analysis was conducted to estimate the impact on GWP results if this consideration were included. Using the FOD model in accordance with IPCC guidelines, methane emissions generated over time from the biodegradable fraction of RDF in a landfill were estimated. It was assumed that approximately 50% of the carbon content in RDF is biogenic and subject to degradation into CH_4 and CO_2 under anaerobic conditions. Subsequently, various landfill gas management scenarios were considered:

- Low: 75% of landfill methane is captured (a high capture efficiency) and 10% of the remainder is oxidized in the cover soil, so only 22.5% of generated methane actually reaches the atmosphere.
- Central: 50% capture, 10% oxidation, so 45% of methane is emitted.
- High: No gas capture, no oxidation (representing an unmanaged dump), so essentially 100% of methane is emitted.

Table 3 below summarizes the GWP for 1 kg of cement in Scenario B, comparing the CH_4 without credit to the CH_4 with the avoided CH_4 credit included, using an IPCC-FOD formulation. Including a landfill CH_4 credit significantly improves the environmental benefits of RDF.

Table 3. GWP sensitivity for Scenario B with avoided-landfill CH_4 credit.

Scenario (1 kg Cement)	GWP_{100} (kg CO_2 eq)
Scenario A	0.993
Scenario B without landfill credit	0.960
Scenario B with landfill credit (central)	0.926
Scenario B with landfill credit (low credit bound)	0.943
Scenario B with landfill credit (high credit bound)	0.885

Using the baseline numbers from the study, Scenario B, without landfill credit, resulted in a 3.3% reduction in GWP, from 0.993 to 0.960 kg CO_2 eq/kg cement due to the substitution of 20% of kiln energy with RDF. Table 3 presents reasonable bounds of 0.943 kg CO_2 eq/kg cement (low-credit) and 0.885 kg CO_2 eq/kg cement (high-credit), highlighting an additional climate value where landfill gas capture is limited and soil oxidation is considered. Figure 4 shows the GWP_{100} per 1 kg cement for the Coal baseline, RDF (20%) without landfill credit, and RDF (20%) with landfill credit (central case).

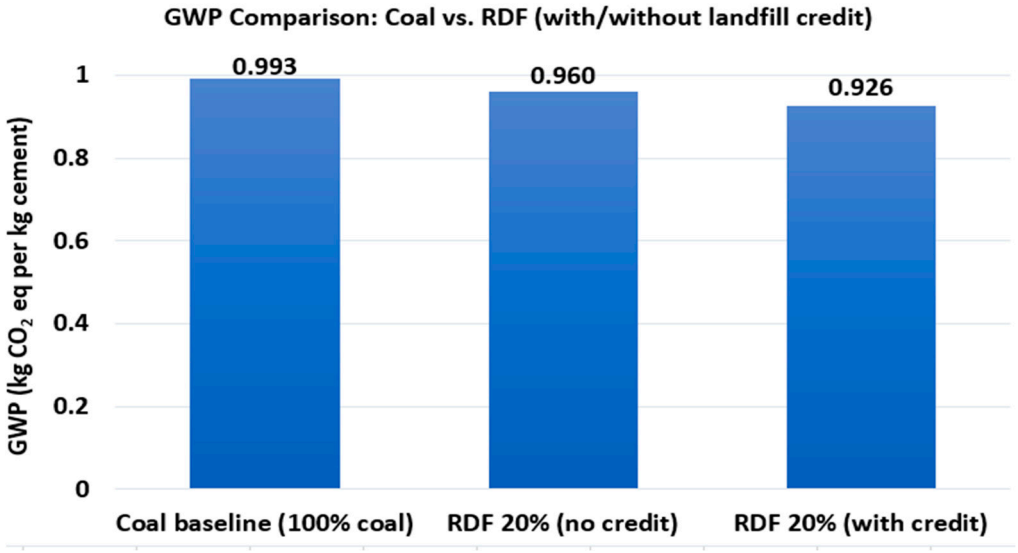

Figure 4. GWP Results for Coal vs. RDF (with/without landfill credit).

With landfill credit, the central GWP of the RDF decreases further to 0.926 kg CO_2 eq/kg cement, as shown in Figure 3, representing a 6.8% reduction compared to coal, with an additional decrease of 0.034 kg CO_2 eq/kg. For context, a typical Portland cement might have around 0.8–0.9 kg CO_2/kg in state-of-the-art operations [15,65,66] when produced with 100% fossil fuels. The base case was a bit higher (0.993) due to 100% coal use and no blending. With RDF and inclusion of the best-case waste credit, the GWP could be reduced to approximately 0.885 kg CO_2 eq per kg of cement, bringing it closer to the 0.8–0.9 benchmark range even in the absence of any clinker reduction. This means that waste co-processing can help close part of the gap to more sustainable cement when viewed in a broader system context. These values include emissions from the cement process and fuel combustion.

Table S3a in the Supplementary Material provides the parameters used to calculate the CO_2 eq credit per kg of RDF diverted from landfills, as well as the credit per functional unit. The values shown in Table 4 indicate that each kg of RDF can save on the order of 0.42–1.88 kg of CO_2 eq emissions from avoided landfill methane, depending on the landfill management efficiency using the IPCC-FOD method (See calculation in Table S3b).

Table 4. Credit per kg of RDF diverted.

Case	Effective Emitted CH_4 Share $(1 - R) * (1 - OX)$	Avoided CH_4 (kg/kg RDF)	Credit (kg CO_2 eq/kg RDF)
Low	0.225	0.015	0.42
Central	0.45	0.034	0.84
High	1.0	0.067	1.88

The results are summarized in terms of CO_2 eq credit/kg of RDF diverted: Low capture avoided methane 0.015 kg CH_4/kg RDF, with the rest captured/oxidized, which is about 0.42 kg CO_2 eq not emitted per kg RDF, and in the central scenario, 0.034 kg CH_4 per kg RDF was avoided, equivalent to 0.84 kg CO_2 eq per kg RDF. High (no capture) avoided 0.067 kg CH_4/kg RDF, equivalent to 1.88 kg CO_2-e per kg RDF.

For the functional unit of 1 kg of cement, 0.04 kg of RDF was used, corresponding to 20% of the 3.3 MJ thermal input, based on an LHV of 20 MJ/kg. Multiplying the per-kg-RDF credits by 0.04 yields the credit per kg of cement (See calculation in Table S3b). Table 5 scales the same credit to the functional unit (1 kg of cement) for the RDF share in the study.

Table 5. Credit per functional unit (1 kg cement; RDF at 20% thermal = 0.04 kg RDF).

Case	Credit (kgCO_2 eq/kg RDF)	RDF per FU (kg/kg Cement)	Credit per 1 kg Cement (kg CO_2 eq)
Low	0.42	4×10^{-5}	0.0168
Central	0.84	4×10^{-5}	0.0336
High	1.88	4×10^{-5}	0.0747

Low scenario: 0.0168 kg CO_2-e avoided per kg cement, essentially negligible at 1.7% of total GWP; Central scenario: 0.0336 kg CO_2 eq avoided per kg cement; High scenario: 0.0747 kg CO_2-eq avoided per kg cement. In the central case, 0.034 kg less CO_2 is produced per kg of cement. That credit was applied to Scenario B, resulting in a GWP decrease from 0.960 to 0.926 kg CO_2 eq per kg of cement. This adjustment increases the effective GWP reduction from 3.3% (without credits) to approximately 6.7% compared to Scenario A. In the high credit case (no capture at landfill), Scenario B's effective GWP drops to 0.885 kg CO_2 eq, roughly an 11% reduction from Scenario A. In the low credit case, which already captures most methane, i.e., 0.943 kg CO_2 eq, a 5% reduction is compared to Scenario A.

This sensitivity analysis shows that including avoided landfill emissions significantly improves the apparent climate benefit of RDF. In a region with limited landfill gas capture, like many African countries currently, the true GWP benefit of using RDF is likely higher than what the cradle-to-gate LCA indicates in this study. The main results excluded this credit to maintain methodological consistency, as attributing such benefits typically requires a separate waste management LCA to avoid double-counting. However, it is essential to note for policy purposes. If a cement plant helps mitigate methane emissions by utilizing waste, there is a strong argument for accounting for this in carbon offset schemes or national greenhouse gas inventories.

4.7. The Sensitivity Analysis of RDF Quality Parameters

Sensitivity analysis was performed on key RDF properties, including biogenic carbon, moisture, chlorine, LHV, and nitrogen content, to assess how RDF quality influences the results. Each parameter was varied individually while keeping total kiln energy constant, adjusting RDF mass as needed. The tests showed that higher biogenic carbon and LHV enhance GWP reduction, while increased moisture, chlorine, or nitrogen slightly diminishes environmental benefits. Overall, RDF performance remains robust across a range of realistic quality levels, as shown in Table S5. Increasing the biogenic carbon share of RDF from 50% to 60% improves the GWP reduction in Scenario B from approximately 3.3% to 4.2%, as more CO_2 emissions become climate-neutral. Lowering it to 40% reduces the benefit to 2–2.5%. Fossil resource depletion remains unchanged because coal displacement is constant. Thus, higher biogenic content enhances climate benefits, while even low-biogenic RDF still achieves equivalent fossil-fuel savings and similar non-GWP impacts. With RDF at 15% moisture, Scenario B achieves a 3.3% GWP reduction. Increasing the moisture level to 25% lowers its calorific value, requiring more RDF to meet kiln energy needs and reducing the GWP benefit to approximately 2.7%. Other impact categories worsen by roughly 1%. Extra transport and combustion of wetter RDF add slight CO_2 burdens, though a net benefit remains. Excessive moisture could negate energy advantages.

Keeping RDF dry maximizes efficiency; each additional percentage of water reduces the heating value and diminishes environmental benefits. With a base RDF chlorine content of 0.3%, increasing it to 0.8%, reflected in more PVC or chlorinated waste, slightly worsened environmental outcomes. Acidification potential rose by about 2%, and photochemical ozone formation by roughly 2%, while other impact categories, such as GWP and particulates, remained unchanged. The kiln's alkaline environment helps neutralize most chlorine, but elevated Cl levels can produce more HCl emissions and increase acid gas formation.

Although the effects are modest, maintaining RDF chlorine below 0.5% is advisable to prevent both environmental and operational issues, such as chloride buildup. Overall, higher chlorine marginally reduces environmental performance, emphasizing the importance of RDF quality control and the separation of PVC materials for optimal kiln operation and minimized emissions. RDF quality, as expressed by its LHV, has a modest influence on environmental performance. When LHV decreased from 20 to 18 MJ/kg, about 11% more RDF was required to meet the same energy demand, reducing the GWP improvement from 3.3% to roughly 2.5% and slightly diminishing other impact benefits (1%).

Conversely, higher-quality RDF at 22 MJ/kg improved GWP reduction to about 3.6%. Thus, a higher LHV enhances performance because each kilogram displaces more coal, although the effect is not dramatic; an 18 MJ RDF still achieves most of its advantages. Typical RDFs, with around 20 MJ/kg, are suitable for cement kilns, whereas very low-calorific waste (10 MJ/kg) would be unsuitable without preprocessing [58,67]. Maintaining adequate calorific value ensures consistent energy efficiency and environmental gains. Nitrogen in RDF has a slight influence on NO_x emissions but does not significantly impact overall effects. Assuming a 5% NO_x increase as baseline, raising it to 10–15% (from nitrogen-rich RDF) increased photochemical ozone formation by about 3% and acidification by roughly 1%, while other categories remained unchanged. Even doubling NO_x emissions caused only minor differences in LCA results. However, high-nitrogen RDF may require stricter NO_x controls, such as SNCR, to meet emission limits, highlighting the importance of proper fuel quality management despite its limited overall environmental impact.

In summary, the sensitivity analyses confirm that the benefits of RDF remain robust across realistic quality ranges. A higher-quality RDF, more biogenic, with a higher LHV and lower chlorine content, improves CO_2 reduction, while lower-quality RDF slightly reduces gains and may marginally increase acidification. However, none of the tested variations reversed RDF's advantage: even the poorest RDF scenario maintained lower GWP than coal and showed only minor differences in other environmental impact categories.

4.8. Economic–Environmental Synergistic Benefits and Policy Integration

This section provides an integrated environmental and economic evaluation of RDF substitution within the cement production system, linking the LCA results with corresponding financial and policy parameters. The analysis quantifies both the environmental performance improvement, expressed as the change in ΔGWP and the associated economic metrics, including cost-effectiveness (CE), net financial impact (ΔΠ), and policy-driven incentives such as carbon taxes and landfill credits. Input parameters and units for the economic–environmental synergistic analysis (South African) are in Table S6a.

Under current South African price signals, RDF substitution simultaneously reduces greenhouse gas emissions and mitigates fuel-related costs. At a substitution rate of 20%, the LCA results indicate a ΔGWP of 0.033 t CO_2/t of cement. The corresponding carbon price benefit is B_{carbon} = 0.432 USD/t, while fuel switching yields a coal saving of 2.277 USD/t compared to the RDF cost of 0.528 USD/t and handling cost of 0.50 USD/t. The results reveal that RDF substitution, although marginally cost-positive at present market rates, demonstrates a clear environmental and economic synergy under South African policy conditions. The equations used, step-by-step calculation and results are in Table S6b. Table S6c summarizes the results in both USD and South African Rand (ZAR), with interpretations.

The net financial impact of 2.87 USD/t (R 52) of cement (without landfill credit) and 2.11 USD/t (R 38) of cement (with landfill credit) corresponds to cost-effectiveness values of 87 (R 1566) and 64 USD/t CO_2 (R 1150) avoided, respectively. These figures confirm that RDF co-processing delivers measurable GHG mitigation benefits while remaining financially competitive under existing carbon tax structures. With landfill credit, the net

financial impact improves to $2.11 per ton of cement, resulting in a decrease in the cost increase from the baseline due to the $0.76/t cement value gained from methane avoidance. While production remains slightly more expensive than the coal-only case, the landfill credit significantly reduces the cost burden, demonstrating how waste diversion incentives can narrow the economic gap for RDF co-processing.

The cost-effectiveness of CO_2 reduction through RDF use was estimated as the cost per ton of CO_2 avoided. Without landfill credit, CE was about $87/t CO_2, meaning the plant effectively pays that amount for each ton of CO_2 avoided. With landfill credit, CE improves to $64/t CO_2. These values, while higher than the current carbon price, are moderate for a hard-to-abate sector like cement. Comparable mitigation options, such as carbon capture, often exceed $100/t CO_2 (R 1800), whereas energy efficiency ranges from $20 to $ 50/t CO_2 (R 360 to 900). Thus, RDF co-processing represents a mid-range abatement cost, reflecting modest emission reduction but additional material-handling costs. The economic analysis indicates a modest cost increase for implementing RDF at the given substitution rate, accompanied by environmental benefits of approximately 33 kg CO_2 per ton of cement. The cost per ton of CO_2 abated remains moderate, meaning the plant pays slightly more to achieve lower emissions and reduced coal dependence. While not yet fully cost-driven, the shift reflects a strategic sustainability investment with clear climate benefits. The results highlight the strategic potential of RDF co-processing as a transitional measure to decarbonize the African cement sector, complementing efforts to reduce the clinker factor, improve energy efficiency, and achieve broader circular economy objectives.

In conclusion, the integrated assessment in this study shows that partial RDF co-firing in cement kilns can modestly reduce emissions and fossil fuel use while maintaining manageable costs, which could be further improved through supportive policy measures. The environmental gains are consistently positive, and economically, RDF use is close to break-even under evolving policy conditions. Thus, RDF co-processing represents a strategically viable solution for African cement plants to lower carbon intensity and advance sustainable waste management within broader decarbonization efforts.

4.9. Limitations and Sources of Uncertainty

This study provides a scenario-based LCA of RDF co-processing and coal combustion in African cement production. However, several limitations demand consideration:

4.9.1. RDF Quality and Regional Variability

While a standardized RDF specification was applied to ensure methodological consistency across both scenarios, this does not capture real-world heterogeneity in RDF properties. Variability in calorific value, moisture content, and contaminant load driven by local waste composition, preprocessing infrastructure, and regulatory maturity can materially influence environmental and economic outcomes. For instance, South Africa benefits from an established waste-to-energy framework [68,69], whereas RDF systems in Ethiopia remain in early development [70]. Prior studies confirm that such differences can significantly affect emission profiles, particularly for sulfur compounds, organics, and chlorine [71,72].

4.9.2. Data Quality, Biogenic Composition, and Landfill Modeling Assumptions

The LCI modeling utilized Ecoinvent v3.7.1, supplemented with country-specific data where available. Nonetheless, some upstream processes, such as RDF preparation and clinker production, rely on global or European proxies, which may misrepresent African-specific energy inputs, emission factors, and process efficiencies. In addition, the biogenic carbon share of RDF was assumed to be 50%, though this can vary from 30% to 60% depending on local segregation practices. Since biogenic CO_2 is excluded from

fossil GWP calculations, this range introduces notable uncertainty into climate impact results. Avoided methane emissions from landfilling were estimated using the IPCC First-Order Decay model, assuming moderate capture rates (50%) and oxidation rates (10%). In practice, many African landfills are open or semi-controlled, implying that actual methane recovery could be significantly lower, which may lead to an overestimation of landfill-related climate credits.

Despite these limitations, the use of harmonized scenarios, grid-normalized controls, and localized energy intensities strengthens the comparative reliability of the results. Nonetheless, the absolute values should be interpreted with caution, and future work should prioritize the integration of locally verified inventory data and field-measured emissions from RDF and landfill systems in Africa.

5. Conclusions

This study demonstrates that substituting coal with RDF in African cement kilns offers measurable environmental and economic advantages under a cradle-to-gate assessment. Using regionally representative data and a standardized LCA framework, the analysis shows that RDF co-processing can reduce GHG emissions, fossil resource use, and certain air pollutants without introducing any significant increases in toxicity or operational risks, provided fuel quality and combustion controls are maintained.

Key results confirm that RDF use reduces net GWP per kg of cement, primarily by displacing fossil carbon with biogenic content and lowering coal demand. However, process emissions from clinker production remain dominant, suggesting that RDF substitution should be part of a broader decarbonization strategy that includes reducing the clinker factor, exploring alternative binders, and implementing energy efficiency upgrades. The benefits are more pronounced in regions where RDF replaces carbon-intensive fuels and landfill methane emissions are unregulated.

From an economic perspective, RDF co-processing appears financially viable when accounting for carbon pricing, landfill diversion incentives, and the avoided costs of fossil fuels. Under current South African policy conditions, RDF substitution can achieve competitive cost-effectiveness levels in the range of USD 64–87 per ton of CO_2 avoided, making it an actionable mitigation control.

5.1. Practical Recommendations

- Scale RDF substitution to 15–30% thermal input where fuel logistics and kiln conditions permit.
- Strengthen RDF supply chains to ensure consistent quality and eliminate hazardous fractions (e.g., e-waste).
- Implement emissions monitoring, especially for NO_x, to manage potential increases in photochemical ozone precursors.
- Integrate RDF with broader strategies, such as SCM utilization, process efficiency, and carbon capture, to maximize lifecycle benefits.

5.2. Limitations and Applicability

- The analysis assumes high RDF combustion efficiency and effective emissions control, which may not hold in all settings.
- Results are sensitive to the composition of RDF, biogenic carbon content, and the local energy grid mix.
- The landfill avoidance credit depends on national waste management practices, which vary widely across African countries.

- Economic performance is contingent on policy incentives such as carbon taxes and landfill tariffs.

Wider adoption of RDF in African cement plants requires coordinated infrastructure development, robust environmental regulation, and cross-sector collaboration with municipalities. Future work should refine country-specific input parameters, explore endpoint impact categories, and conduct techno-economic feasibility studies across varied market contexts. RDF represents a practical step toward low-carbon industrial growth aligned with circular economy and climate policy goals.

5.3. Policy Implications and Recommendations

To facilitate RDF co-processing in cement production, targeted policy interventions are needed in both South Africa and Ethiopia. In South Africa, the existing National Waste Management Strategy (2020) and the Carbon Tax Act can be harnessed to incentivize RDF adoption through landfill diversion credits and emissions-based tax relief. Establishing national RDF quality standards and streamlining permitting processes would further reduce implementation barriers. In Ethiopia, developing RDF supply chains through municipal–private partnerships and providing fiscal support for kiln adaptation and emissions control are critical. In both countries, aligning RDF initiatives with Nationally Determined Contributions (NDCs) could attract climate finance and reinforce national climate commitments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/sci7040184/s1, Table S1. Inventory Inputs and Outputs data for Scenario A and B [7,14,15,20,38,39,41,55,57,73–80]; Table S2. RDF Definition, Properties, and Sensitivity Ranges [7,18,20,58,67,81–93]; Table S3a. Key assumptions and input data [94–97]; Table S3b. Sensitivity Calculation: avoided landfill methane credit; Table S4. Uncertainty Analysis Results; Table S5. The sensitivity of RDF parameters; Table S6a. The Input Parameters and Units for Economic–Environmental Synergistic; Table S6b. The Calculation: Economic–Environmental Synergistic; Table S6c. The Results of The Economic–Environmental Synergy of RDF Substitution (USD and ZAR equivalents); Table S7. Native-grid results by country for Scenario A and Scenario B (values per 1 kg of cement).

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