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Environmental Sustainability of Calcined Iron Ore Production: A Life Cycle Assessment and Scenario Analysis

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Abstract

Calcined iron ore production is of strategic importance; however, it is associated with considerable environmental burdens due to its high carbon footprint. In this study, the environmental impacts of calcined iron ore production were evaluated using a cradle-to-gate life cycle assessment (LCA) approach. The assessment was conducted using the ReCiPe 2016 Midpoint (H) V1.13 methodology, the Ecoinvent 3.12 database, and SimaPro 10.5.0.3 software. In addition, four alternative scenarios were developed to investigate potential strategies for reducing environmental impacts. The results identified the calcination stage as the dominant environmental hotspot across most impact categories. Calcination accounted for 98.8% of the total global warming potential, 99.1% of the terrestrial acidification potential, and 99.3% of the fine particulate matter formation potential. Scenario analysis revealed that technological interventions focusing on a single parameter were unable to simultaneously reduce all environmental impacts and, in some cases, introduced additional environmental trade-offs. Scenario 4, which involved the substitution of the kiln fuel with natural gas, achieved substantial reductions in air quality-related impact categories. Nevertheless, due to the predominance of process-related emissions, the reduction in global warming potential was limited to 15.77%. Scenario 2, incorporating photovoltaic-based electrification, reduced dependence on fossil energy sources but resulted in increased ecotoxicity impacts associated with the photovoltaic panel supply chain. Based on these findings, a hybrid strategy combining natural gas utilization in the calcination process with the electrification of open-pit mining and crushing–screening operations is proposed as a promising pathway for improving the environmental performance of calcined iron ore production. Overall, the proposed hybrid system could reduce emissions by 145 kg CO_2 eq per tonne of product (19.5%), strengthening the long-term environmental and economic performance of calcined iron ore production.

Keywords: calcination; iron; life cycle assessment; sustainability; green mining

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1. Introduction

Iron is extensively used across a wide range of industries, including construction, transportation, and automotive manufacturing, owing to its relatively low cost and high mechanical strength. Iron ore is the primary raw material for iron and steel production. Driven by global industrial development, iron demand has increased substantially over the past century, resulting in a corresponding growth in iron production [1,2]. Global reserves of run-of-mine iron ore are estimated at approximately 200 billion tonnes, of

which Türkiye accounts for around 0.08% [3]. Türkiye ranks seventh worldwide in crude steel production, with an annual output of approximately 38.1 million tonnes, and is the largest crude steel producer in Europe [4]. The continued expansion of iron and steel production has consequently increased the generation of solid, liquid, and gaseous emissions throughout the production chain, making their environmental implications an increasingly important concern.

Calcination is one of the thermal processes employed in iron production and involves the treatment of carbonate-bearing minerals, such as siderite, at elevated temperatures (550–1150 °C) to remove carbonate species [5]. Iron production encompasses several stages, including mining, ore beneficiation, and calcination, which require substantial inputs of water, raw materials, fuels, electricity, and explosives and generate process-related emissions and wastes. These resource requirements and environmental releases make the iron and steel industry one of the major contributors to industrial environmental impacts. LCA is widely employed to quantify and evaluate the environmental impacts associated with such emissions and resource consumption. LCA is a standardized scientific methodology for systematically assessing the environmental impacts of products, processes, or activities throughout their life cycles [6,7]. By providing a holistic perspective on resource consumption and environmental burdens, LCA supports more informed decision-making in both industry and public policy [8]. A key strength of LCA is its ability to simultaneously evaluate multiple environmental impact categories across the life cycle of a product or process. LCA results can therefore be used to identify environmental hotspots and guide improvements in production systems. Accordingly, the application of LCA in the mining and metallurgical sectors has increased considerably in recent years [9].

According to ISO 14040 and ISO 14044 standards, an LCA study comprises four main phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [10]. Existing LCA impact assessment methods can broadly be classified into three groups: midpoint-oriented, endpoint-oriented, and combined midpoint–endpoint approaches. In midpoint-oriented methods, inventory data are translated into impact categories such as global warming, acidification, and eutrophication. Endpoint-oriented methods, in contrast, aggregate environmental impacts into areas of protection, including resource depletion, damage to human health, and ecosystem damage. Although endpoint approaches provide a broader representation of environmental damage, midpoint approaches generally offer greater methodological precision and lower uncertainty in impact characterization [11]. In the present study, the ReCiPe impact assessment method, which integrates midpoint and endpoint perspectives, was employed to provide a comprehensive assessment of both the environmental impacts and associated damage outcomes of iron production.

Depending on the system boundary and the life cycle stages considered, LCA studies may adopt cradle-to-grave, cradle-to-gate, cradle-to-cradle, or gate-to-gate approaches. The cradle-to-grave approach encompasses the entire life cycle of a product or process, from raw material extraction through production, use, and final waste treatment. The cradle-to-gate approach covers the stages from raw material extraction to the production of the final product at the factory gate. When materials or products are recovered and returned to the production cycle at the end-of-life stage, the system is generally described as a cradle-to-cradle approach [12].

The international literature contains numerous LCA studies addressing the production of metallic minerals and industrial raw materials, including copper, zinc, nickel, and aluminum, as well as cement, gypsum, coal, and steel. However, LCA studies on iron production that explicitly incorporate mining operations remain relatively limited. One cradle-to-gate study in Brazil reported that grinding was the major contributor to impacts

on human health and ecosystems in the production of iron concentrate using flotation [13]. A study in Australia identified loading and hauling operations as the largest contributors to greenhouse gas emissions during iron ore production [12]. A study conducted in China found that agglomeration and ore processing were the dominant sources of greenhouse gas emissions in iron concentrate production [14]. In another study conducted in China, the life cycle assessment of pellet iron production was investigated, and it was reported that the largest greenhouse gas emissions originated from the pelletizing stage, where a rotary kiln similar to calcination was utilized [11]. Another study in Brazil, the environmental impacts of flotation followed by pelletizing during iron ore beneficiation were evaluated. The results showed that pelletizing, which requires substantial inputs of coal, fuel oil, natural gas, and electricity, contributed significantly to several impact categories, including ecosystem climate change, stratospheric ozone depletion, photochemical oxidant formation, terrestrial acidification, freshwater eutrophication, land transformation, and fossil resource scarcity [15].

Previous studies have focused on life cycle assessment or specific stages of the production process. However, the environmental impacts of calcined iron ore production have not been comprehensively evaluated at an industrial scale while considering different scenarios. This study addresses this research gap by quantitatively assessing the environmental impacts of the industrial-scale calcined iron ore production process using a life cycle assessment approach. It also aims to provide a comparative reference framework for future research.

2. Materials and Methods

2.1. Goal, Scope, Functional Unit and System Boundary

This study evaluated the life cycle environmental impacts of calcined iron ore production using production and consumption data obtained from an industrial-scale calcination plant operating in the Eastern Anatolia Region of Türkiye. Four alternative scenarios were developed to assess potential strategies for reducing environmental impacts, with the production of 1 tonne of calcined iron ore defined as the functional unit. The LCA was conducted using the SimaPro 10.5.0.3 software and the Ecoinvent 3.12 database, with the ReCiPe 2016 Midpoint (H) V1.13 method applied for life cycle impact assessment [16,17].

The system boundary was defined using a cradle-to-gate approach. The production system comprises three main stages: (i) open-pit mining, including the extraction of run-of-mine ore at the mine site; (ii) crushing and screening; and (iii) calcination, during which the processed ore is converted into calcined iron ore (Figure 1). This study was conducted solely for academic research purposes, and the data and results are not intended for commercial use.

2.2. Data Sources

The life cycle inventory (LCI) was developed based on the production and consumption data for 2024 from the mine, ore processing, and calcination facilities associated with the plant. Inventory data were obtained from the company's production and operational records. During data collection, a wide range of inputs associated with the calcined iron ore production process were considered, including the fuel consumption of trucks, loaders, excavators, and other mobile equipment used at the production facilities; the quantity of explosives used in open-pit mining; the amount of run-of-mine (ROM) ore produced; and the electricity consumption of crushers and screens used in the ore preparation facilities. Consumable materials, such as lubricating and grease oils used for motor vehicles, crushers, conveyors, and trucks to enhance their operational efficiency and service life, were

also included in the study. In addition, the quantities of electricity, natural gas, and coal consumed in the calcination plant were included in the assessment.

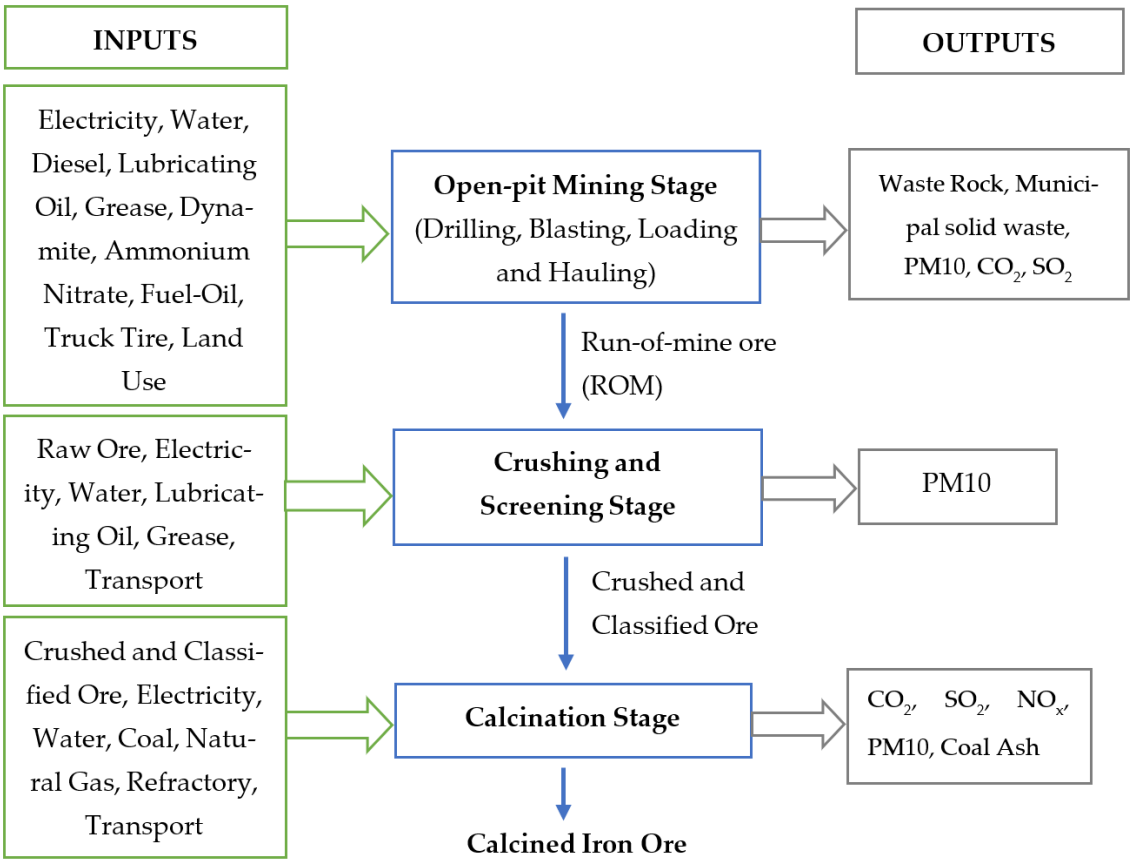


Figure 1. System boundarys for life cycle assessment of calcined iron ore production.

Solid waste generated across all facilities, electricity consumption associated with conveyor belt systems, land occupation for stockpile areas, and other facility-related uses, and the quantity of municipal solid waste were also included in the calculations. The pedigree matrix was employed to evaluate the reliability, representativeness, and overall quality of the collected data. The system boundaries of the study are presented in Figure 1. The pedigree matrix was applied to assess the reliability, representativeness, and overall quality of the collected data [18].

The coal used as fuel in the calcination kiln is imported from Russia and fed to the kiln after grinding. During calcination, 4–14 mm iron ore is sequentially processed through the preheater, rotary kiln, and rotary cooler to upgrade the grade of the low-grade carbonate-bearing iron ore and improve product quality. Consequently, the Fe content of the siderite feed ore increases from 37–39% to 54–56%, resulting in the production of calcined iron ore.

The main equipment used throughout the mining and calcined iron ore production chain was included within the system boundary shown in Figure 1. The open-pit mining operation comprises 60 haul trucks, 5 loaders, and 3 drilling machines, whereas the crushing and screening plant includes two crushers, namely, primary and secondary crushers. The calcination plant consists of ore feeding, preheating, a horizontal rotary kiln, a hot gas generator (HGG), a heat exchanger, a rotary cooler, calcined ore handling, and coal grinding units.

Blasting operations were conducted once a week in the open pit mine. For the calculations, it was assumed that the dust generated during blasting is dispersed over a one-hour period. The dust generated during blasting was not included in the calculated total PM10

emissions because its mass flow is intermittent and because delay detonators are used and the ground was watered before and after blasting, which substantially limits dust generation and dispersion.

2.3. Life Cycle Inventory (LCI)

When Türkiye-specific datasets were unavailable in the Ecoinvent database, "Rest of World (ROW) | Cut-off, U" datasets were used as the first alternative, followed by "Global (GLO) | Cut-off, U" datasets when ROW data were also unavailable. The "market" datasets were selected for inventory modeling because they account both production and associated logistics and transportation activities. In accordance with ISO 14044, a 1% mass- and energy-based cut-off criterion was applied [19]. Accordingly, the energy consumption of administrative buildings, facility lighting, employee transportation to and from the site, spare parts for mobile equipment (e.g., brake pads and filters), drill-bit consumption, waste generated from blasting detonators, and crusher and mill liners were excluded from the system boundary because their individual contributions to the total system impact were considered negligible (<1%).

The facility does not conduct direct measurements of greenhouse gas or particulate matter emissions. Therefore, the CO_2 and SO_2 emissions associated with the thermal decomposition of carbonate-bearing iron ore and coal combustion, respectively, were estimated using the stoichiometric mass-balance approach (Tier 3) specified by the IPCC (2006) [20]. The calculations were based on the chemical compositions of the run-of-mine and calcined iron ore presented in Table 1 and the imported coal presented in Table 2. The Tier 3 approach was selected because plant-specific chemical analysis data were available (Tables 1 and 2). Had the simpler Tier 1 approach been used, process CO_2 emissions from ore calcination would have been estimated at 598.3 kg using the relevant EPA AP-42 emission factor. This value was found to be 16% higher than the value validated using the plant-specific stoichiometric mass balance. Complete combustion of the coal under sufficient oxidation conditions was assumed, with all carbon released from both coal combustion and the thermal decomposition of the ore assumed to be fully converted to CO_2. Accordingly, intermediate combustion products such as CO were not considered in the emission calculations.

Table 1. Chemical analysis results of raw ore and calcined iron ore.

	ROM Iron	Calcined Iron		ROM Iron	Calcined Iron
Fe%	37.92	55.48	K_2O%	0.11	0.18
C%	9.57	0.96	Na_2O%	0.03	0.04
Mn%	3.62	5.29	Zn%	0.02	0.03
MgO%	3.55	5.14	TiO_2%	0.01	0.02
CaO%	2.26	3.29	Cu%	0.01	0.01
SiO_2%	1.85	2.75	P%	0.01	0.02
Al_2O_3%	0.30	0.46	Pb%	0.00	0.00
S%	0.16	0.16	As%	0.00	0.00
$Na_2O + K_2O$%	0.13	0.22	LOI%	32.64	1.44

Table 2. Chemical analysis results of imported lignite.

Fixed Carbon %	C %	O %	H %	N %	S %	Ash %	Volatile Matter %
60.87	74.28	6.42	3.98	2.15	0.28	11.7	27.43

As the ore contains no nitrogen, NO_x (nitrogen oxides) emissions during calcination were attributed entirely to coal combustion and the thermal oxidation of atmospheric nitrogen [21]. Because NO_x formation is strongly dependent on combustion technology

and temperature, NO_x emissions were estimated using the emission factors for industrial coal combustion published by the U.S. Environmental Protection Agency (EPA) in AP-42, rather than by a stoichiometric mass-balance approach [22]. Similarly, direct measurement of instantaneous exhaust emissions from mobile sources (i.e., heavy-duty equipment) during open-pit mining operations was not feasible. Therefore, CO_2 and SO_2 emissions associated with diesel fuel consumption were estimated using the relevant EPA AP-42 emission factors. In addition, because direct, site-specific, continuous monitoring data for particulate matter emissions from open-pit mining activities were unavailable, PM10 emissions from crushing and screening operations and haulage on unpaved roads were estimated using EPA AP-42 emission factors [23].

Land use impacts were quantified using site-specific data. Based on the physical extent of the iron ore deposit (1400 × 300 m) and the areas allocated for overburden removal, an operational footprint of approximately 42 ha was estimated to be required. Using the total estimated reserve of 47 million tonnes, the land transformation and land occupation impacts associated with the production of 1 tonne of calcined iron ore were quantitatively assessed.

For the LCA inventory of calcined iron ore production, site-specific data were used to quantify the inputs required to produce 1 tonne of calcined iron ore, including energy, water, raw materials, explosives, lubricants, and vehicle tires, as well as the associated emissions and product outputs. These calculations were performed separately for the open-pit mining (Table 3), crushing and screening (Table 4), and calcination (Table 5) stages.

Table 3. Life cycle inventory of the open-pit mining stage for the production of 1 ton of calcined iron ore.

Inputs		**Outputs**	
Energy and Materials	**Quantity**	**Energy and Materials**	**Quantity**
Diesel	1.77 kg	ROM iron ore	1.577 ton
Tap water	82 kg	Waste rock	3.1 ton
Lubricating oil	0.00035 kg	Municipal solid waste	0.627 kg
Grease	0.00154 kg	PM10 (Loading and hauling)	0.00701 kg
Ammonium Nitrate *	0.3188 kg	CO_2 (from diesel combustion)	5.60 kg
Fuel-Oil *	0.0204 kg	SO_2 (from diesel combustion)	0.0099 kg
Dynamite	0.0061 kg		
Truck tire	0.011 kg		
Transformation for mining	0.0141 m^2		
Occupation, mineral extraction site	1.062 m^2a		

* A total of 0.3392 kg of ANFO was used for blasting (Ammonium nitrate/fuel oil (ANFO) 94% AN and 6% FO [12].

Table 4. Life cycle inventory data for the crushing and screening stage in the production of 1 tonne of calcined iron ore.

	Energy and Materials	**Quantity**
Inputs	ROM iron ore	1.577 ton
	Electricity (Crushers and screens)	3.943 kWh
	Tap water	1.6 kg
	Lubricating oil	0.009 kg
	Grease	0.028 kg
	Transport (with truck)	6.3 tkm
Outputs	Crushed iron ore	1.575 ton
	PM10	0.0096 kg

Table 5. Life cycle inventory of the calcination stage for the production of 1 ton of calcined iron ore.

	Energy and Materials	Quantity
Inputs	Crushed iron ore	1.575 ton
	Electricity	41.27 kWh
	Coal (lignite)	55 kg
	Natural gas (for HGG unit)	2.79 m^3
	Refractory	1.66 kg
	Tap water (for cooling)	110 kg
	Transport (with truck)	11.025 tkm
	Transport (with conveyor belt)	4 tkm
Outputs	Calcined iron ore	1 ton
	PM10	0.26 kg
	Solid waste (coal ash)	6.44 kg
	CO_2 (from coal and natural gas)	149.80 kg
	CO_2 (from iron ore)	517.47 kg
	NO_x (from coal)	0.16 kg
	SO_2 (from coal and iron ore)	2.148 kg

2.4. Uncertainty Analysis

According to ISO 14040-14044, uncertainty analysis is a systematic approach for quantitatively assessing the combined effects of uncertainties associated with the model, datasets, and input parameters on environmental results [24]. Monte Carlo simulation, which is widely used to assess uncertainty in LCIA results, is also implemented in LCA software, such as SimaPro [25]. In this study, Monte Carlo simulation was employed to estimate uncertainties in the life cycle inventory data. Uncertainty analysis was performed for inventory data derived from EPA AP-42 emission factors, assuming a lognormal probability distribution. Although the operational data are subject to measurement and representativeness uncertainties, Monte Carlo simulation was applied only to PM10 and NO_x emissions. Furthermore, uncertainties related to ore composition and coal consumption were excluded from the quantitative analysis scope due to the limited availability of routine intra-year facility laboratory measurements, particularly concerning the chemical compositions of run-of-mine ore and calcined product, as well as the heating value and carbon content of imported coal. The analyses was conducted using 1000 iterations at a 95% confidence interval. The PM10 and NO_x emissions calculated according to the EPA AP-42 guidelines were evaluated using a 1000-iteration Monte Carlo simulation, and the results are presented in Figure 2.

The amount of PM10 generated during the production of 1 tonne of calcined iron ore in the calcination stage was estimated to fall within the range of 0.241–0.301 kg at the 95% confidence level. The analysis results indicated a relatively homogeneous distribution of the emission estimates, with a mean and median of 0.27 kg and a coefficient of variation (CV) of 5.56%. Similarly, the amount of NO_x generated during calcined iron ore production was estimated to range from 0.143 to 0.179 kg with 95% confidence. The uncertainty analysis results indicate that uncertainties in the inventory inputs do not materially affect the stability and statistical robustness of the final environmental impact results obtained from the LCA. The low coefficients of variation further support the representativeness and reliability of the calculated emission data.

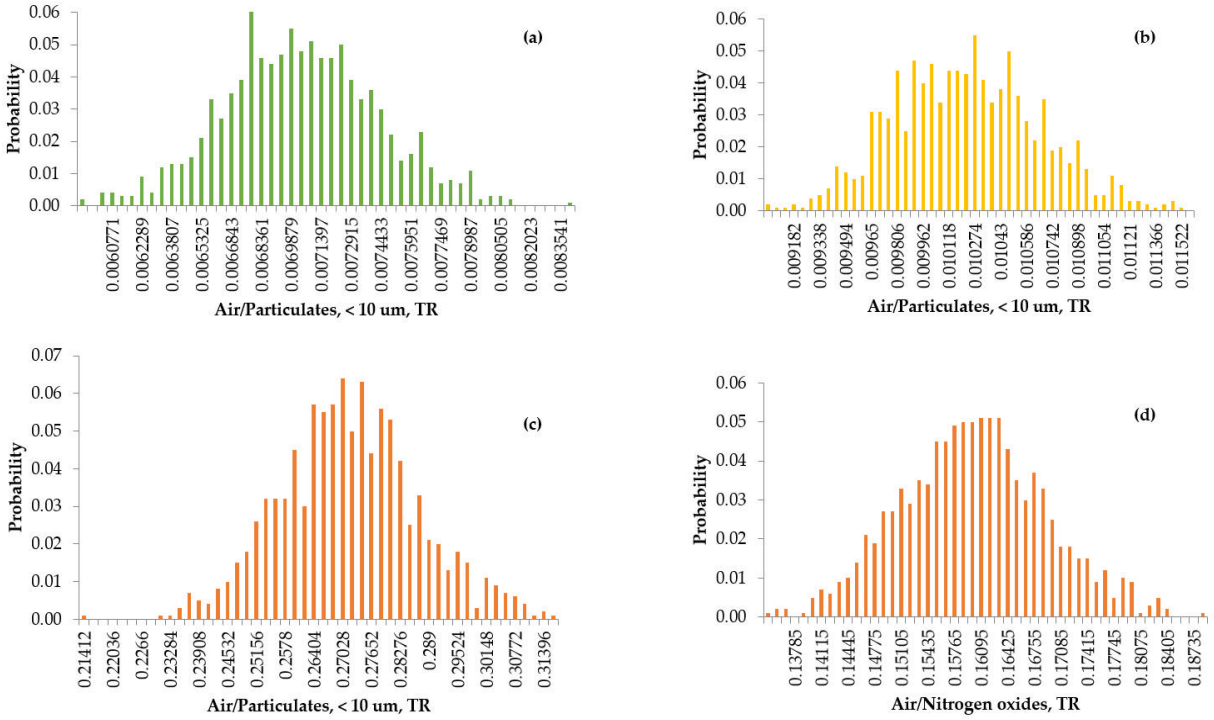


Figure 2. Uncertainty analysis of open-pit mining stage PM10 (**a**); crushing and screening stage PM10 (**b**); calcination stage PM10 (**c**) and calcination stage NO_x (**d**) (confidence interval: 95%).

3. Results and Discussion

3.1. Life Cycle Impact Assessment (LCIA)

Fossil fuel consumption in the iron and steel industry significantly increases its carbon footprint [26–28]. In this study, the environmental burdens associated with the production of 1 tonne of calcined iron ore were evaluated across key midpoint impact categories, including global warming, acidification, eutrophication, and ecotoxicity. The LCIA results for calcined iron ore production are presented in Figure 3 and Table 6.

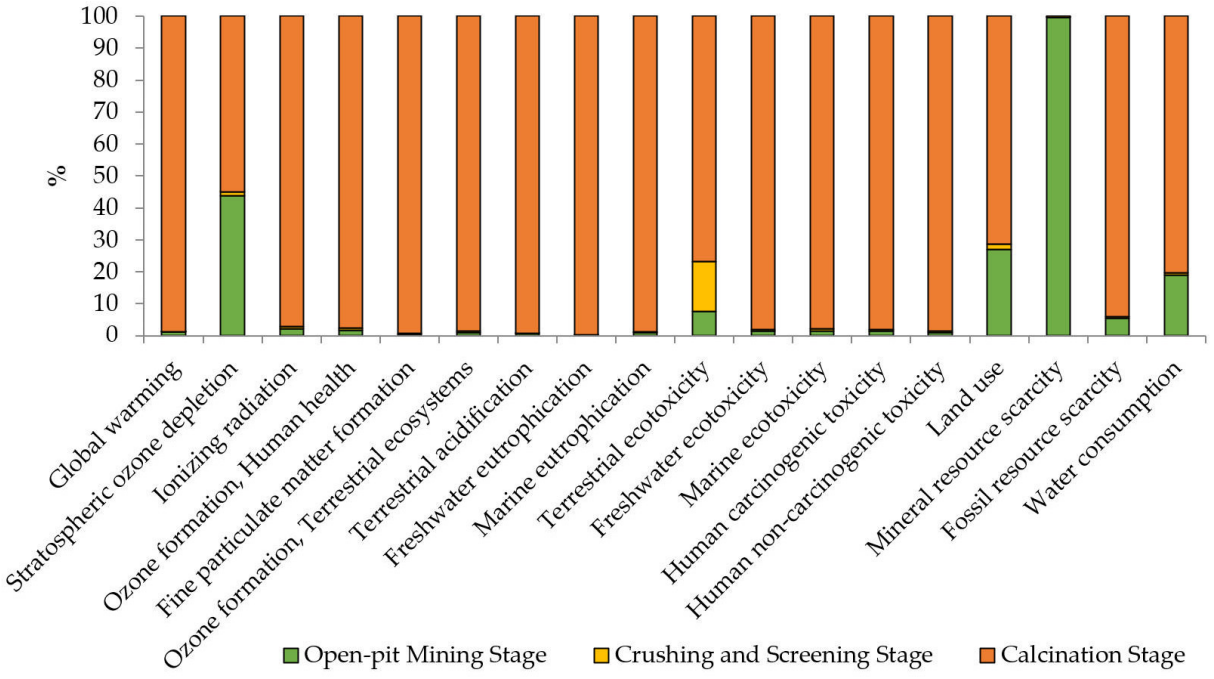


Figure 3. Life cycle impact assessment results for the production of 1 tonne of calcined iron ore.

Table 6. Results of the LCIA for the production of 1 ton of calcined iron ore.

Impact Category	Unit	Open-Pit Mining Stage	CrushingScreening Stage	Calcination Stage	Total
Global warming	kg CO_2 eq	8.45	0.784	733	742
	%	1.14	0.106	98.8	100
Stratospheric ozone depletion	kg CFC11 eq	1.24×10^{-5}	3.46×10^{-7}	1.56×10^{-5}	2.84×10^{-5}
	%	43.9	1.22	54.9	100
Ionizing radiation	kBq Co-60 eq	0.0315	0.00926	1.36	1.4
	%	2.26	0.663	97.1	100
Ozone formation, Human health	kg NO_x eq	0.00645	0.00258	0.379	0.388
	%	1.66	0.664	97.7	100
Fine particulate matter formation	kg PM2.5 eq	0.00593	0.000809	0.91	0.917
	%	0.646	0.0883	99.3	100
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.00778	0.00285	0.709	0.719
	%	1.08	0.396	98.5	100
Terrestrial acidification	kg SO_2 eq	0.0167	0.00164	2.14	2.16
	%	0.774	0.0763	99.1	100
Freshwater eutrophication	kg P eq	0.000343	0.000131	0.119	0.12
	%	0.286	0.109	99.6	100
Marine eutrophication	kg N eq	8.31×10^{-5}	1.14×10^{-5}	0.00731	0.0074
	%	1.12	0.154	98.7	100
Terrestrial ecotoxicity	kg 1,4-DCB	5.45	11.4	55.6	72.5
	%	7.51	15.8	76.7	100
Freshwater ecotoxicity	kg 1,4-DCB	0.0559	0.0215	3.77	3.84
	%	1.45	0.56	98	100
Marine ecotoxicity	kg 1,4-DCB	0.0766	0.0339	5.19	5.3
	%	1.45	0.641	97.9	100
Human carcinogenic toxicity	kg 1,4-DCB	0.142	0.0507	9.21	9.41
	%	1.51	0.539	97.9	100
Human non-carcinogenictoxic.	kg 1,4-DCB	1.41	0.713	149	151
	%	0.932	0.473	98.6	100
Land use	m^2a crop eq	0.841	0.0534	2.22	3.11
	%	27	1.72	71.2	100
Mineral resources scarcity	kg Cu eq	27.6	0.00204	0.0924	27.7
	%	99.7	0.00735	0.334	100
Fossil resource scarcity	kg oil eq	2.49	0.284	43.1	45.8
	%	5.44	0.619	93.9	100
Water consumption	m^3	0.0927	0.00346	0.395	0.491
	%	18.9	0.704	80.4	100

The LCA results demonstrated that the calcination stage was the dominant source of environmental burdens across all impact categories. Calcination accounted for 98.8% of the global warming potential, primarily due to the process emissions generated during the decomposition of carbonate-bearing ore. The calcination stage also exhibited the highest contribution to stratospheric ozone depletion, ionizing radiation, ozone formation, fine particulate matter formation, acidification, and eutrophication. Similar to the contribution of furnace-based processing stages to the overall carbon footprint of the iron and steel industry, the calcination stage represents the most significant contributor to the environmental

burden of the calcined iron ore production system [15,26]. In contrast, the contributions of open-pit mining and crushing–screening remained limited across all impact categories. N_2O emissions associated with the production of ammonium nitrate, a key component of ANFO, which is widely used as an explosive in open-pit mining, are particularly relevant because N_2O is a potent greenhouse gas and an important contributor to stratospheric ozone depletion [29,30].

The network diagrams demonstrated that the environmental burdens associated with the calcination stage were driven not only by direct emissions from the kiln but also, to a substantial extent, by indirect impacts arising from the production and supply chains of coal, grid electricity, refractory materials, and natural gas.

Emissions from the calcination stage constitute major hotspots, particularly in terms of global warming, acidification, and fine particulate matter formation. The supply chains associated with imported coal and domestic electricity generation also contribute substantially to environmental impacts related to stratospheric ozone depletion, ionizing radiation, ozone formation, eutrophication, toxicity, and ecotoxicity. Overall, fossil fuel consumption and its associated supply chains were identified as the most critical factors governing the environmental performance of the production calcined iron ore.

According to the life cycle impact assessment results, the global warming impact associated with the production of 1 tonne of calcined iron ore was calculated as 742 kg CO_2 eq. Of this impact, 733 kg CO_2 eq, corresponding to 98.8%, is attributable to the calcination stage. A combined examination of the network diagram and process inventory data indicates that 89.9% of the global warming impact within the calcination stage itself originates from process-related emissions released during the decomposition of carbonate-bearing ore in the calcination kiln. The indirect (background) environmental burdens associated with the calcination stage in the global warming category arise primarily from the supply chain of imported coal used in the kiln (including its production and transportation), accounting for 4.72%, and from the generation of grid electricity consumed at the facility, accounting for 3.13%. The contribution of the open-pit mining stage to the overall global warming impact was relatively limited at 1.14%, while that of the crushing and screening stage was only 0.106%.

Calcination is a high-temperature thermochemical process and therefore requires more energy than conventional ore beneficiation, which is based primarily on physical or chemical methods. In this study, the greenhouse gas emissions from calcined iron ore production were estimated to be 742 kg CO_2 eq. This value exceeds the 13.32 kg CO_2 eq reported for open-pit mining and flotation [13], as well as the values reported for pelletizing and sintering [11,14,15]. Higher emissions reflect both the substantial heat demand of calcination and the process of CO_2 release during the decomposition of carbonate ores. The estimated value was lower than the emissions reported for basic oxygen furnace (BOF; 2459 kg CO_2 eq) and electric arc furnace (EAF; 913 kg CO_2 eq) steel production [28]. Therefore, calcined iron ore production represents a thermochemical pretreatment stage between ore beneficiation and final metal production. Its emissions of 742 kg CO_2 eq should be considered an additional contribution to the overall environmental burden of the iron and steel production chain.

The fine particulate matter formation category accounts for both directly emitted primary PM2.5 from industrial activities and secondary PM2.5 formed through atmospheric chemical reactions involving SO_2 and NO_x, which generate sulfate and nitrate aerosols. Fine particulate matter (PM2.5) refers to particles with an aerodynamic diameter of $\leq$2.5 μm. Owing to their small size, these particles can penetrate deeply into the human respiratory system and therefore pose substantial risks to human health [17,31]. In our study, the environmental burden associated with the production of 1 tonne of calcined iron ore in the

fine particulate matter formation category was calculated as 0.917 kg PM2.5 eq. Of this impact, 99.3% is attributable to the calcination stage, while 0.65% originates from open-pit mining. The contribution of the crushing and screening stage was negligible, accounting for only 0.09% of the total impact. Within the calcination stage, 73.5% of its contribution to fine particulate matter formation is directly attributable to emissions generated in the calcination kiln. Of the remaining contribution within the calcination stage, 19.5% is associated with the indirect impacts of locally generated electricity supplied by a thermal power plant, while 3.82% arises from the production and supply chain of imported coal.

Acidification generally occurs when NO_x and SO_2 in the atmosphere react with water vapor and O_2 to form sulfuric acid (H_2SO_4) and nitric acid (HNO_3) [32]. Acidification in aquatic ecosystems can create adverse environmental conditions and disrupt ecosystem functions [33–35]. Eutrophication is an important environmental impact resulting from the accumulation of nitrogen and phosphorus in aquatic ecosystems, which can promote algal proliferation, oxygen depletion, and biodiversity loss [36,37]. NO_x and SO_2 emissions associated with fossil fuel use in iron and steel production can increase eutrophication potential [38]. SO_2 induced acidification can increase phosphate solubility, thereby facilitating its transfer to surface waters and indirectly contributing to eutrophication [39].

The terrestrial acidification impact associated with the production of 1 tonne of calcined iron ore was calculated as 2.16 kg SO_2 eq. Of this impact, 2.14 kg SO_2 eq, corresponding to 99.1%, is attributable to the calcination stage. Within the calcination stage, 90% of its contribution to terrestrial acidification is directly associated with emissions generated in the kiln. Of the remaining contribution within the calcination stage, 4.7% is attributable to the indirect impacts associated with locally generated electricity from thermal power plants, while 3.5% originates from the production and supply chain of imported coal. Domestic lignite- and hard-coal-fired power plants used for grid electricity generation increase the acidification burden primarily through SO_2 emissions in flue gases released during fuel combustion. In contrast, imported coal contributes to the acidification burden not only through mining operations but also through NO_x emissions from transport equipment during long-distance rail and maritime transportation. The freshwater eutrophication impact associated with the production of 1 tonne of calcined iron ore was calculated as 0.12 kg P eq, while the corresponding marine eutrophication impact was 0.0074 kg N eq. The calcination stage accounted for 99.6% of the freshwater eutrophication impact and 98.7% of the marine eutrophication impact.

The terrestrial ecotoxicity impact was estimated at 72.5 kg 1,4-DCB eq, with 76.7% of the total impact attributed to calcination, 15.8% to crushing–screening, and 7.5% to open-pit mining. The principal contributors to the environmental burden of the calcination stage were imported coal, diesel used for ore transportation, and grid electricity. The impacts associated with crushing–screening were primarily attributable to diesel consumption for ore transportation, whereas ammonium nitrate production, diesel consumption, and blasting activities were the dominant sources of environmental burdens during open-pit mining.

The freshwater and marine ecotoxicity impacts were estimated at 3.84 and 5.3 kg 1,4-DCB eq, respectively. In both categories, approximately 98% of the total environmental burden originated from the calcination stage, while the contributions of open-pit mining and crushing–screening remained negligible. Network analysis indicated that the impacts associated with calcination were largely driven by the production, logistics, and waste-rock management processes of imported coal, as well as upstream processes associated with domestic lignite used for grid electricity generation. These findings highlight the critical role of heavy-metal emissions arising throughout fossil fuel production and supply chains in determining aquatic ecotoxicity.

The human carcinogenic toxicity and human non-carcinogenic toxicity impacts were estimated at 9.41 and 151 kg 1,4-DCB eq, respectively. In both impact categories, the majority of the environmental burden originated from the calcination stage, accounting for 97.9% and 98.6% of the total impacts, respectively. Network diagrams indicated that these impacts were primarily associated with the production and supply chain of imported coal used in the kiln, together with upstream processes related to domestic lignite used for grid electricity generation. The results demonstrate that both direct and indirect fossil fuel use are major determinants of human toxicity impacts in calcined iron ore production. These pollutants can accumulate in air, water, and soil, enter the human body through multiple exposure pathways, and potentially cause more severe effects through bioaccumulation [40–42].

The land use category represents the environmental impacts of production activities associated with land occupation and land transformation and is commonly expressed in m^2.year (m^2a) or m^2 crop eq [17,43]. In this study, the total land use impact was estimated at 3.11 m^2a crop eq. Of this impact, 71.2% was attributable to calcination, 27.0% to open-pit mining, and 1.72% to crushing–screening. The main contributors to land use during calcination were indirect land requirements associated with the supply chains of imported coal and thermally generated electricity, whereas the land use impacts of the mining stage were primarily associated with ore extraction and stockpiling activities. These findings indicate that fossil fuel consumption and raw material production are key drivers of land use impacts.

Mineral resource scarcity represents the potential reduction in the future availability of mineral resources consumed during production [44,45]. According to the model results, the mineral resource scarcity impact associated with the production of 1 tonne of calcined iron ore was 27.7 kg Cu eq, of which 99.7% (27.6 kg Cu eq) originated from iron ore extraction during open-pit mining. Fossil resource scarcity represents the environmental pressure associated with the consumption of non-renewable energy resources such as coal, oil, and natural gas [46–48]. This impact was estimated at 45.8 kg oil eq per tonne of calcined iron ore, with 93.9% attributable to calcination and 5.44% to open-pit mining. The major contributions during calcination were associated with imported coal and electricity consumption, whereas diesel use was the dominant contributor during mining. These results demonstrate that the energy-intensive calcination process is the primary driver of fossil resource consumption.

Water consumption is an LCA impact category representing the net consumption of freshwater resources within production systems and their associated supply chains [17,49,50]. According to the model results, water consumption associated with the production of 1 tonne of calcined iron ore was estimated at 0.491 m^3. Of this total, 80.4% was attributed to calcination, 18.9% to open-pit mining, and 0.7% to crushing–screening. During calcination, the main contributors were electricity generation, cooling water, and the coal supply chain, whereas water used for dust suppression was the dominant contributor during mining. Overall, the results demonstrate that calcination constitutes the principal environmental hotspot in the system, not only in terms of human health, climate change, and ecosystem impacts but also with respect to water consumption. In contrast, the contributions of open-pit mining and crushing–screening remained comparatively low.

3.2. Sensitivity Analysis

Sensitivity analysis provides a scientific basis for evaluating environmental impacts. Accordingly, a sensitivity analysis was conducted across all impact categories for calcined iron ore production. A revised inventory was developed by reducing the relevant parameters reported in Tables 3–5 by 5%, and the resulting environmental impacts were recalculated.

As shown in Figure 4, a 5% reduction in water consumption and grid electricity use improved the water consumption category by 4.49%. A 5% reduction in electricity consumption also resulted in improvements exceeding 2.0% in toxicity and eutrophication. Reducing coal and diesel inputs by 5% improved fine particulate matter formation by 1.88%, stratospheric ozone depletion by 2.61%, and global warming by 0.31%. The limited improvement in the global warming category indicates that the climate impact of calcined iron ore production is driven more by carbonate ore than fuel inputs.

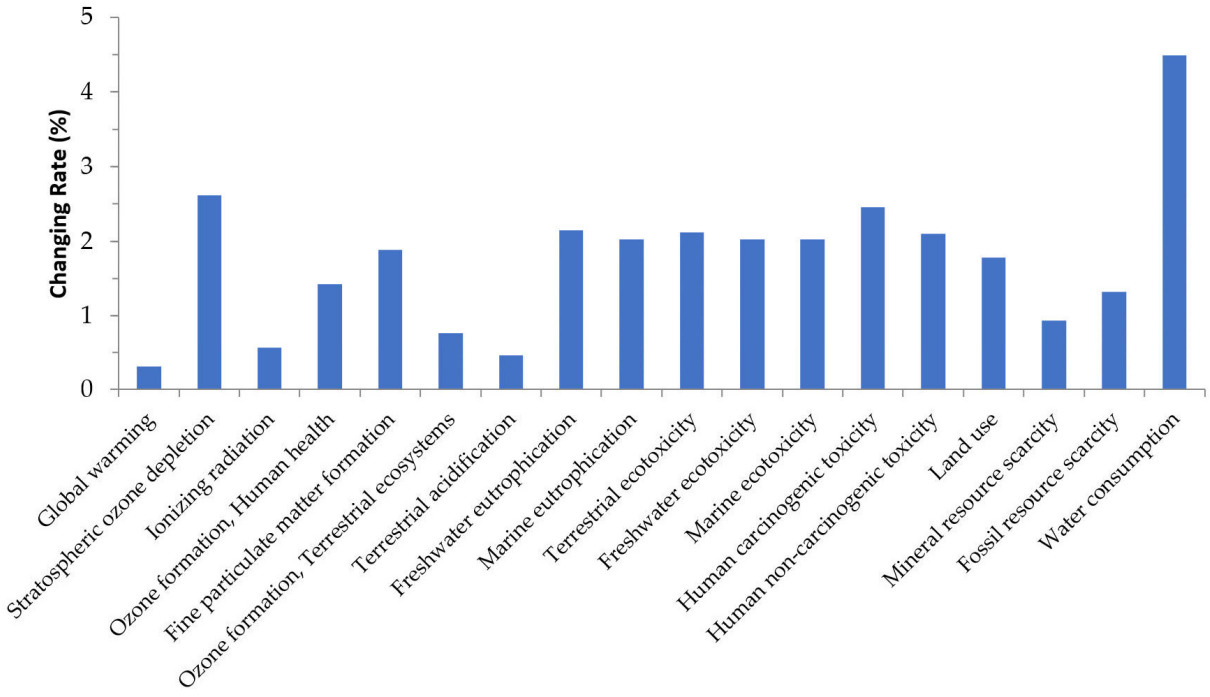


Figure 4. Sensitivity analysis results.

3.3. Scenarios

Scenario 1: In this scenario, the use of green petroleum coke (petcoke) instead of lignite as the fuel in the calcination stage was modeled. The thermal energy requirement for producing 1 tonne of calcined iron ore was assumed to remain constant, and the required amount of petcoke was calculated as 27 kg, corresponding to the energy supplied by 55 kg of coal. For CO_2 emissions, process-related emissions were assumed to be identical (517.47 kg), while CO_2 emissions from petcoke combustion were calculated as 93.06 kg based on an assumed carbon content of 87%. SO_2 emissions were estimated at 3.1 kg assuming a sulfur content of 8% in petcoke [51]. Using the emission factors specified in the EPA AP-42 guidelines, NO_x and PM10 emissions were estimated at 0.08 and 0.13 kg, respectively. While the use of lignite generated 6.44 kg of waste ash, the corresponding amount was reduced to 0.14 kg when petcoke was used. Although this scenario provides environmental benefits, its implementation would require substantial plant modifications and capital expenditure (CAPEX). These modifications include the integration of dedicated multi-channel burners to adapt the rotary kiln to petcoke, modification of the grinding mill to enable finer grinding, reinforcement of refractory linings to withstand higher flame temperatures and sulfur-induced corrosion, and installation of a sulfur-removal unit in the rotary kiln flue-gas line to mitigate the acidification impacts associated with increased SO_2 emissions from petcoke combustion. In Scenario 1, imported coal is substituted with green petroleum coke while maintaining the total thermal energy required for the calcination reaction. The operational effects of fuel switching on the in-furnace temperature distribution, combustion kinetics, and specific flue-gas treatment requirements are treated

as technical constraints of the scenario. The scenario assumes that the total heat supplied to the furnace remains constant because petroleum coke has a higher calorific value, and less fuel is required on a mass basis.

Techno-economic analyses, including cost-effectiveness and payback-period assessments, were not conducted because comparable and verifiable capital and operating cost data were unavailable for the specified scenarios.

Scenario 2: This scenario modeled the replacement of diesel-powered heavy-duty equipment used in open-pit mining, including haul trucks, drilling machines, and excavators, with fully electric alternatives, together with supplying the entire electricity demand of the crushing–screening and calcination plants from a newly installed photovoltaic (PV) power plant. Accordingly, diesel consumption in the open-pit mining stage was assumed to be zero. The lower heating value of the 1.77 kg of diesel reported in the inventory in Table 3 was converted into an equivalent electricity demand of 7.96 kWh. Electricity consumption for the crushing–screening and calcination plants was set at 3.943 and 41.27 kWh, respectively, as reported in Tables 4 and 5. For this scenario, it was assumed that the continuous electricity supply required to operate a 24/7 heavy industrial facility could be provided by solar energy without intermittency constraints. This scenario would also require substantial initial capital investment due to the replacement of the vehicle fleet, installation of the PV power plant, and additional on-site equipment requirements. To ensure a continuous 24-h electricity supply from the photovoltaic (PV) system, an appropriately sized battery energy storage system (BESS) must be integrated. Excess electricity generated during peak solar irradiance periods is stored and discharged during periods without generation, such as nighttime, to meet the plant's electricity demand. The BESS capacity should be sized to fully meet the calcination plant's daily energy demand and operational load requirements.

Scenario 3: In Scenario 3, 20% of the diesel fuel demand of the equipment used in open-pit mining was modeled to be replaced with biodiesel produced from waste vegetable oil. Accordingly, 20% of the 1.77 kg diesel requirement reported in the inventory in Table 3 was assumed to be substituted with biodiesel. The use of 100% biodiesel was not considered for the open-pit mining stage because of the increased risk of fuel gelling under winter conditions and the potential implications for heavy-duty equipment engine warranties; therefore, biodiesel substitution was limited to 20% [52]. Consequently, the fossil diesel requirement was reduced to 1.416 kg biodiesel requirement was estimated at 0.354 kg. The emissions calculated based on these fuel quantities are presented in Table 7.

Table 7. Emission values used in Scenario 3.

	Emissions from Fossil Origin Diesel Combustion	**Emissions from Biogenic Origin Diesel Combustion**
CO_2 (kg)	4.48	0.991
SO_2 (kg)	0.00792	0.0000071

Scenario 4: In Scenario 4, the use of natural gas instead of lignite as the primary fuel in the calcination kiln was modeled. The thermal energy supplied by the 55 kg of imported coal reported in the inventory in Table 5 was converted to an equivalent natural gas demand, resulting in a required natural gas consumption of 27 m^3. For the calculation of CO_2 emissions, process-related emissions were maintained at 517.47 kg, consistent with the inventory data reported in Table 5. The emissions associated with the consumption of 27 m^3 of natural gas are presented in Table 8. Switching from coal to natural gas eliminates mechanical abrasion caused by coal ash. This is expected to extend refractory service life and reduce refractory consumption per tonne of product. Accordingly, for Scenario 4, the refractory value reported in Table 5 was reduced by 20%, resulting in a consumption of

1.328 kg. Although this scenario allows for the decommissioning of facilities such as the coal mill and coal storage yard and provides environmental benefits through the cleaner, ash-free combustion of natural gas, it requires significant upfront capital expenditure (CAPEX) for the necessary equipment, including a pressure reduction and metering station, safety valve assemblies, and multi-channel burners designed for natural gas.

Table 8. Emission values used in Scenario 4.

CO_2 (kg)	SO_2 (kg)	NO_x (kg)
51.91	0.00026	0.0432

The LCIA scenario results are presented in Figure 5. In Scenario 1, replacing lignite with petcoke reduced CO_2, SO_2, NO_x, PM10, and ash emissions, resulting in substantial improvements in the toxicity and resource scarcity categories. Human carcinogenic and non-carcinogenic toxicity impacts decreased by 65.57% and 72.85%, respectively, while freshwater and marine ecotoxicity were reduced by approximately 72%. As a refinery by-product, petcoke requires less additional mining, reducing the fossil resource scarcity impact from 45.8 to 18 kg oil eq (60.7% reduction) and the land use impact to 1.54 m^2a crop eq (50.48% reduction). Conversely, its high sulfur content increased terrestrial acidification to 2.89 kg SO_2 eq (33.8% increase) and fine particulate matter formation to 1.16 kg PM2.5 eq (26.5% increase), representing the highest values among the evaluated scenarios. These findings indicate that petcoke use can provide advantages in terms of toxicity and resource consumption but may increase environmental burdens associated with acidification and particulate matter formation.

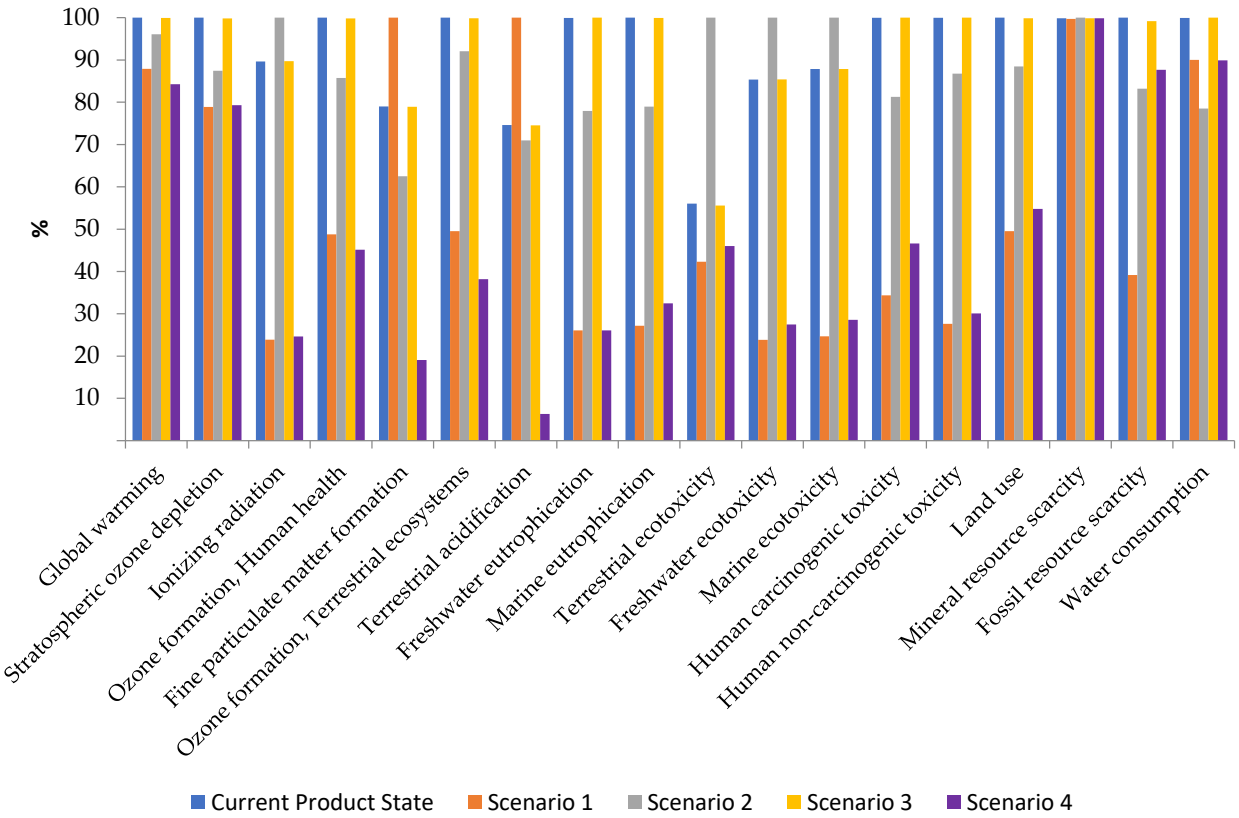


Figure 5. Comparison of impact assessment results for the different scenarios of 1 tonne calcined iron ore production.

In Scenario 2, the transition to solar-generated electricity and electric mining equipment reduced water consumption to 0.381 m^3, the lowest value among all scenarios. The elimination of diesel-related emissions also reduced fine particulate matter formation to 0.725 kg PM2.5 eq, corresponding to a 20.94% reduction. However, the supply chains of photovoltaic panels and lithium-ion batteries resulted in the highest terrestrial ecotoxicity impact, reaching 129 kg 1,4-DCB (77.94% increase). Similarly, the highest environmental burdens for freshwater ecotoxicity (4.50 kg 1,4-DCB), marine ecotoxicity (6.03 kg 1,4-DCB), and ionizing radiation (1.56 kBq Co-60 eq) were observed in this scenario. These results demonstrate that renewable energy integration and electrification can reduce water consumption and particulate emissions while potentially increasing ecotoxicity and ionizing radiation impacts associated with due to processes stemming from the supply chain.

Scenario 3 exhibited an environmental impact profile largely comparable to that of the baseline production system. The benefits achieved through biodiesel use in open-pit mining remained limited relative to the dominant environmental burden associated with intensive coal consumption in the calcination kiln. Global warming (742 kg CO_2 eq) and fine particulate matter formation (0.916 kg PM2.5 eq) remained unchanged from the baseline, while no meaningful changes were observed in key categories such as human carcinogenic toxicity (9.41 kg 1,4-DCB) and freshwater ecotoxicity (3.84 kg 1,4-DCB). Although this scenario offers relatively high implementation feasibility because it does not require major additional equipment, its potential for environmental improvement is limited.

In Scenario 4, the transition to natural gas provided substantial improvements, particularly with respect to air emissions and climate change. Terrestrial acidification decreased by 91.57% to 0.182 kg SO_2 eq, while fine particulate matter formation decreased by 75.90% to 0.221 kg PM2.5 eq. The global warming impact decreased to 625 kg CO_2 eq, corresponding to a 15.77% reduction, while the elimination of ash generation reduced human carcinogenic toxicity by 53.35% to 4.39 kg 1,4-DCB. These results demonstrate that natural gas use can provide a lower-emission production profile compared with the baseline system, particularly for air quality-related impact categories.

Among the scenarios evaluated, the combined implementation of Scenarios 2 and 4 is expected to provide the greatest environmental benefit. Accordingly, an LCIA was conducted for this hybrid production system, and its results were compared with those for the current production system in Figure 6.

The proposed hybrid production system yields substantial environmental improvements, reducing impacts by 60–96% across the air quality, human health, ecotoxicity, and acidification categories. The increase in terrestrial ecotoxicity associated with the PV and equipment supply chains represents the system's only notable environmental trade-off. Switching to natural gas reduced impacts in the fine particulate matter formation and terrestrial acidification categories by 96.3% and 96.4%, respectively, while lowering global warming potential by 19.5% (Figure 6). The comparatively modest reduction in global warming potential reflects the substantial contribution of process emissions from ore decomposition. This indicates that fuel-focused scenarios have limited potential to reduce the system's global warming impact.

Excluding carbon capture, utilization, and storage (CCUS) technologies, the proposed hybrid production system appears to be an effective approach for minimizing the environmental impacts of calcined iron ore production. From an economic perspective, replacing coal-fired systems and ash-disposal infrastructure with natural-gas burners generally requires relatively minor modifications to industrial furnaces. The unit energy cost of natural gas varies relative to imported coal, depending on fuel prices and global market fluctuations. However, the operational advantages and lower maintenance requirements of natural gas may partly offset this price difference, particularly when the costs of flue-gas desulfuriza-

tion (FGD), exhaust-gas treatment, fuel storage, ash disposal, and maintenance associated with coal use are considered. Although the transition to natural gas and photovoltaic (PV) electrification may increase capital expenditure (CAPEX), these costs could be partly offset by the higher thermal efficiency of electric equipment, declining PV levelized costs of electricity (LCOE), and reduced expenses for coal-ash handling and flue-gas management. As the Carbon Border Adjustment Mechanism (CBAM) and national emissions trading systems are implemented, carbon costs are expected to affect final product prices directly. The hybrid system's estimated carbon reduction of 145 kg CO_2 eq per tonne of product (19.5%) could lower the plant's exposure to carbon costs, thereby reducing long-term unit production costs and strengthening its competitive position.

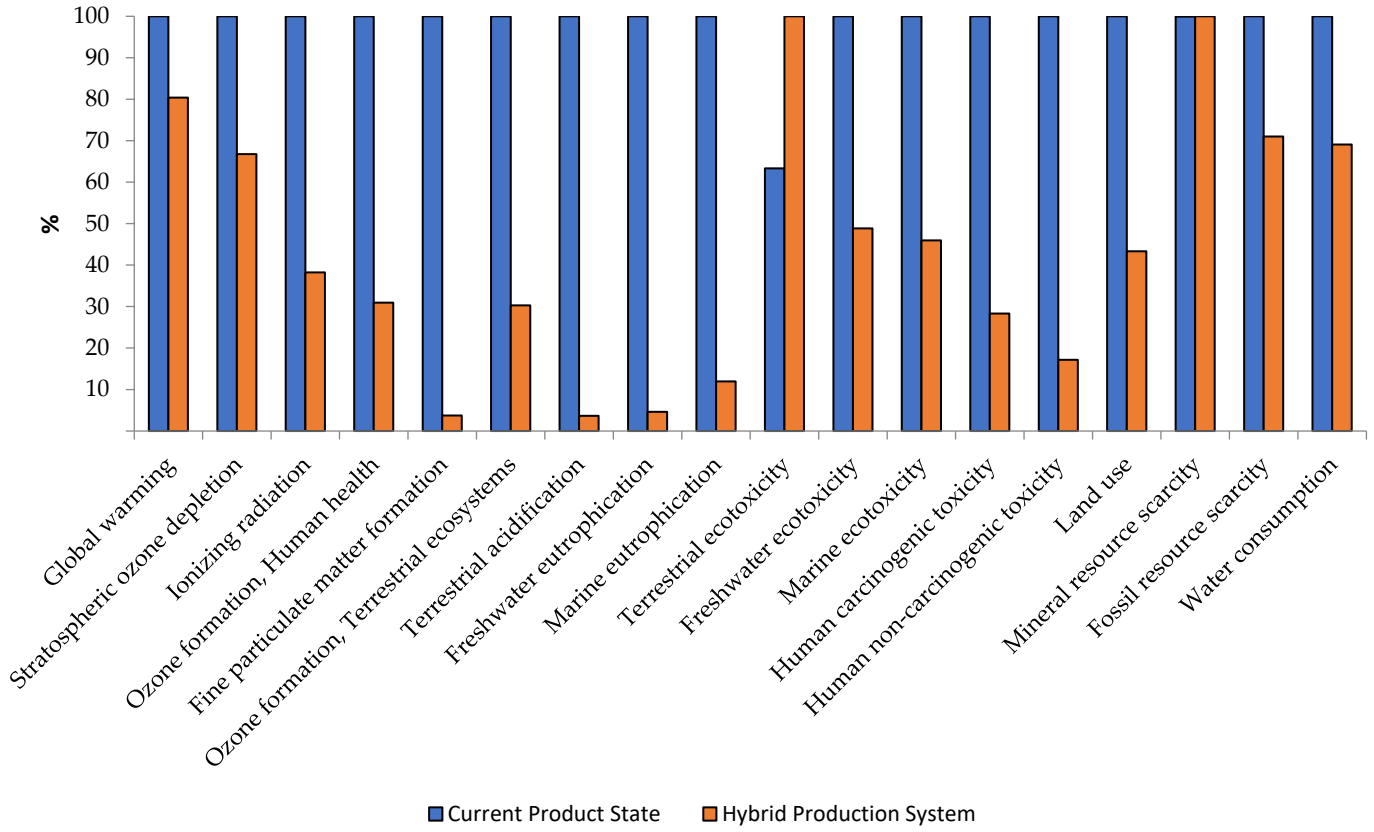


Figure 6. Comparison of impact assessment results for Current Product State and Hybrid Product System.

4. Conclusions

Fossil fuels, such as coal, petroleum, and natural gas, used in the production of calcined iron ore are associated not only with greenhouse gas emissions but also with the release of various pollutants that directly contribute to air, water, and soil contamination. In this study, the cradle-to-gate environmental impacts of producing 1 tonne of calcined iron ore were evaluated. The results demonstrated that the environmental burden was overwhelmingly concentrated in the calcination stage. Calcination was identified as the principal hotspot for global warming (98.8%), terrestrial acidification (99.1%), fine particulate matter formation (99.3%), freshwater eutrophication (99.6%), and marine eutrophication (98.7%). In contrast, open-pit mining was the dominant stage for mineral resource scarcity, accounting for 99.7% of the total impact, whereas the overall contribution of the crushing–screening stage remained negligible.

Scenario analysis demonstrated that improvements based on a single parameter do not necessarily eliminate the overall environmental burden but may instead shift impacts among different categories. Scenario 4 (natural gas) provided substantial improvements in

air emissions and climate change impacts, whereas Scenario 1 (petcoke) offered advantages in terms of toxicity and fossil resource scarcity but increased acidification and particulate matter formation. Scenario 2 (PV-based electricity and electrification) achieved the best performance in terms of water consumption and particulate matter formation but increased ecotoxicity impacts associated with equipment supply chains. Scenario 3, in contrast, exhibited an environmental profile largely comparable to that of the baseline production system. The hybrid system's emission reduction of 145 kg CO_2 eq per tonne of product (19.5%) could lower carbon-related costs, thereby reducing long-term unit production costs and strengthening competitiveness.

Based on these findings, a hybrid approach combining natural gas use for calcination with PV-supported electricity generation is considered the most balanced option for reducing the overall environmental burden. The integration of a heat exchanger and hot gas generator (HGG) unit can improve energy efficiency, resulting in fuel savings of approximately 10–15% in the rotary kiln system, consequently reducing its environmental burden. However, to achieve further long-term environmental improvements, the integration of carbon capture technologies, such as calcium looping (CaL), amine scrubbing, oxy-fuel combustion, and mineral carbonation, could further contribute to reducing process-related CO_2 emissions, which represent the dominant source of the overall climate impact.

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