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Life Cycle Assessment (LCA) of Refuse-Derived Fuel as a Partial Substitute for Coal in Cement Production: A Case Study in Valle del Cauca, Colombia

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Abstract

Substitution of fossil fuels in cement kilns with refuse-derived fuels (RDF) has received widespread attention, driven by the need to reduce emissions as well as to improve economic feasibility. Cement kiln installations in Colombia have reported the coprocessing of different waste in their operation. Yet, no information regarding the potential environmental benefits of incorporating an alternative fuel was found. Therefore, in this study, an LCA is developed for a hypothetical cement plant located in Valle del Cauca, Colombia, comparing the partial substitution of coal for RDF, in terms of potential reduction of environmental impacts, to the baseline scenario. Inventory results showed the main contributor to CO2 emissions is limestone decomposition. The LCA results showed a 6 % decrease in CO2 emissions in the process with partial substitution. Yet, other categories showed a reduction of approximately 20 %, consistent with the coal reduction percentage, indicating that substituting RDF for coal could reduce impacts from the cement industry.

Keywords

Life cycle assessment; LCA; Sustainability; Cement industry; Refuse-derived fuels; RDF.

Registration

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Análisis de ciclo de vida (ACV) de la incorporación de combustible derivado de residuos como sustituto parcial de carbón en la producción de cemento en un contexto del Valle del Cauca, Colombia

Resumen

La sustitución de combustibles fósiles en hornos cementeros por combustible derivado de residuos (CDR) ha recibido amplia atención, no solo para reducir emisiones, sino también como alternativa para mejorar la factibilidad económica. Las fábricas de cemento en Colombia han reportado el coprocesamiento de diferentes residuos en su operación. No obstante, no se encontró información con respecto a los potenciales beneficios ambientales de esta práctica. Por lo tanto, en este estudio se desarrolla un ACV para una planta hipotética de producción de cemento ubicada en el Valle del Cauca, Colombia, en la cual se sustituye parcialmente el carbón por CDR, y se compara en términos de la potencial reducción de impactos ambientales, con el proceso que usa únicamente carbón. Los resultados del inventario mostraron que la principal contribución a las emisiones de CO2 es la descomposición de la caliza. Los resultados del ACV indicaron una disminución de 6% de las emisiones de CO2 en el proceso con CDR. Sin embargo, otras categorías mostraron una reducción del 20 % consistente con la reducción del porcentaje de consumo de carbón, lo que indica que la sustitución parcial puede potencialmente reducir los impactos ambientales de la industria del cemento.

Palabras clave

Análisis de ciclo de vida, ACV, Sostenibilidad, Industria del cemento, Combustible derivado de residuos, CDR.

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1. Introduction

The Global Cement and Concrete Association (GCCA) 2050 cement and concrete Industry roadmap for net zero concrete is the collective commitment of member companies to improve sustainability in the sector (GCCA, 2022). This roadmap distinguishes as primary strategies to address climate change the electrical and energetic efficiency, the use of alternative fuels and the clinker/cement ratio. Under GCCA guidelines, a roadmap was established in Colombia towards carbon neutrality up to 2050 for cement and concrete industry, posing significant technical challenges to accomplish the proposed goals for years 2030 and 2050 (Cámara Colombiana del Cemento y Concreto, 2021). One of the proposed actions for carbon dioxide emissions reduction is the incorporation of alternative fuels in clinker production as well as the utilization of waste as raw materials for cement and concrete.

Several studies have highlighted the advantages of incorporating alternative fuels in cement production not only from an environmental but also an economic point of view (Tihin et al., 2023; Uddin et al., 2023). For example, Gebreslassie, Bahta and Mihrete (2023) assessed biomass wood, bark and leaves from a local tree as well as recycled tires to replace up to 40 wt.% coal consumption in cement production in Ethiopia, and reported CO2 and SO2 emissions reductions up to 17 % and 95 %, respectively. Similar findings were reported by Kukreja, Soni, Mohapatra, and Panda (2023) in the impact assessment of alternative fuels on production costs, plant operation and environment in five Indian cement production plants using alternative fuels from biomass, plastic waste, hazardous waste and mixed waste. Their findings showed not only positive results in terms of CO2 mitigation potential due to the use of alternative fuels, but also its contribution to reducing production cost associated with the increase of substitution ratio.

Dinga & Wen (2022) studied a roadmap to assess China's proposed goal to achieve carbon neutrality by 2050 and concluded that achieving such goal is challenging but possible under aggressive abatement scenarios including carbon capture and storage measures, alternative fuels derived from biomass, used tires and sludges, renewable energy adoption and the implementation of advanced efficiency technologies. Georgiades, Steubing, Cheeseman and Myers (2023) assessed CO2 emissions mitigation potentials to decarbonize cement production, including clinker substitution, alternative fuels, kiln improvement and carbon capture and storage using prospective LCA. A mitigation of 25 % of CO2 emissions was reported for alternative fuels, and up to 88% included all the alternatives, which was sufficient to meet the target reductions.

2. Theoretical framework

Fossil fuel substitution by alternative fuels derived from municipal solid wastes (MSW), known as refuse-derived fuels (RDF), has received widespread attention not only to mitigate carbon dioxide emissions and increase economic feasibility in cement production, but also as a reliable alternative for mitigating methane emissions and other well-known impacts from landfills management (Kosajan et al., 2021). RDF production from MSW involves different unit processes to remove noncombustible and potentially recyclable fractions such as metals, glass and plastics as well as the humid or putrescible organic fractions, generally followed by size and humidity reduction of the remaining fractions of plastic, paper and Tetrapak, leather and fabrics, miscellaneous waste biomass and wood. Table 1 indicates RDF yields, defined as mass of produced RDF to mass of waste processed, and heating value obtained from MSW in different locations depending on the initial composition and the fractions removed and processed to obtain the product. Yields as low as 19 and as high as 84.1 % are reported, depending on the removal or not of non-compostable biomass fractions. Whereas the exclusion of biomass fractions has advantages related to the elimination of a humidity reduction step and a higher heating value, it has disadvantages not only from the considerably reduced yield but also from the inferior environmental benefits that can be obtained from burning RDF since CO2 emissions from biomass fractions can be considered Carbon-neutral emissions, which means a zero global warming potential (GWP). Therefore, RDF CO2 mitigation potential is directly related to the non-compostable biomass fractions in the waste such as waste vegetables, paper, wood and wool fabrics.

Table 1.
RDF yields and heating values reported in literature

RDF yield (%)	Heating value LHV (MJ/kg)	Comments/ localization	Reference
84.1	17.2	with non-compostable organic/Iran	(Salaripoor et al., 2025)
24.6	23.8	without non compostable organic/Iran	(Salaripoor et al., 2025)
50.1	20.5	MSW from industrial sector with reduced organic content/ Korea	(Dong & Lee, 2009)
52.8-39.9	15.8-19.4	Without organic/Vancouver	(Reza et al., 2013)
19-25	14-22	Without organic/Ghana	(Sarquah et al., 2025)

Note: The authors

Several authors have assessed the environmental benefits of incorporating RDF as a partial fossil fuel substitution by means of life cycle assessment. Gäbel & Tillman, (2005) developed a model for LCA analysis of cement production from cradle (raw materials extraction and processing) to gate (cement production from clinker and additives). By means of simulation 9 different scenarios were analyzed, comprising recovery of materials as well as the incorporation of RDF. It was shown that both strategies contributed to emission reductions of CO2, NOx, SO2, CO, VOC, CH4 and dust from 30 to 80%. Pitre, La and Bergerson, (2024) proposed a LCA model from cradle to gate to estimate the greenhouse gasses emission and criteria air contaminants as well as the impact of biogenic carbon accounting when using an alternative fuel derived from landfill wastes to substitute 50% of natural gas in cement production in Alberta, Canada. The results showed a reduction of 7-13% of greenhouse gases, which was dependent on the method of accounting CO2 emissions. By assuming Carbon-neutral emissions (GWP=0), a 7% reduction was estimated, whereas the inclusion of forest growth and rotation periods on wood production and final disposal resulted in 13 % reductions due to negative carbon dioxide emissions (GWP<0).

Georgiopoulou & Lyberatos (2018) assessed the environmental impacts of using alternative fuels to substitute 10 % fossil fuels in cement production by means of LCA to determine which was the most environmentally friendly scenario. Considered alternative fuels included RDF, TDF (tire derived fuel), BS (Biological sludge) and mixtures between them. The analysis was done from cradle to gate (clinker production) and LCA software Simapro was used for the model construction and analysis. The results showed the most favorable scenario was the substitution for RDF, whereas the least favorable was the scenario with biological sludge.

Salaripoor, Yousefi and Abdoos (2025), estimated the environmental impacts of the use of RDF as partial fossil fuel substitution during natural gas shortages in colder months in Teheran (Iran). The authors used the software OpenLCA and Ecoinvent database, considering the available information for cement production in North America was valid for Iran, since both rely on natural gas for cement production. The study examined two RDF compositions, including organic compostable waste and one excluding it, to determine their impact on sustainability and fuel efficiency. Key findings indicated that RDF when produced with organic waste offers substantial reductions in global warming potential (GWP) and other environmental impacts compared to conventional fuels. Specifically, the results demonstrated that RDF can significantly lower CO2 emissions associated with cement production, positioning it as a viable option for enhancing energy sustainability within industry.

In the Colombian context, cement production companies have reported in their sustainability reports the incorporation of different wastes such as tires, impregnated hydrocarbons, RDF and biomass, by means of coprocessing in the cement kiln to substitute coal consumption in their operation. Yet, no information was available regarding the estimation of the environmental benefits in terms of emission reductions accomplished through a life cycle assessment considering not only the cement production but also the subprocess related to alternative fuels production and valorization. In addition, no readily available information was found regarding RDF production from MSW in large Colombian cities. Therefore, in this study the potential environmental benefits of the incorporation of RDF produced from MSW in a cement production factory are assessed by means of a life cycle model developed in LCA free software OpenLCA, in which the current scenario in Colombia, cement production using exclusively carbon as fossil fuel, is compared to the alternative scenario of substitution of 20 wt.% coal for an equivalent amount of RDF in terms of heating value. A hypothetical cement plant production industry located in the municipality of Yumbo, Valle del Cauca, was proposed, considering that in this region are located two large cement production companies due to the existence of mineral and energetic resources required, and are also located in the route of the MSW collection and disposal in the sanitary landfill that serves the city of Cali.

3. Methodologies

This study follows the principles of Environmental Management-Life Cycle Assessment ISO 14040/14044, (2006) and The International Reference Life Cycle System (ILCD) handbook. Accordingly, a LCA consists of four stages: goal and scope, life cycle inventory (LCI) impact assessment and interpretation. An account of the current cement production process and the production of RDF from MSW is provided next.

3.1. Current cement production technology in Valle del Cauca

Cement plants located in Valle del Cauca use the cement production technology known as new suspension preheater (NSP), which was developed in Japan and imported to China, where more than 80 % of cement production plants use this technology. Therefore, it is safe to assume that a new production plant to be implemented in Colombia would make use of this technology. NSP technology as described in Li et al., (2015) consists of three primary production processes: The pulverized coal and raw meal preparation process, which includes transferring, grinding, homogenizing, and storage of raw materials, and the grinding and storage of coal. In the burning process, the ground and mixed raw materials are input to the preheater, and then to the calciner, decomposing with 60 % of coal at 950 °C. The limestone decomposes for about 95 % in the calciner and 5 % in the kiln. The decomposed materials fall into the kiln and are incinerated to be clinker with 40 % of coal at a temperature of over 1,400 °C. In the finishing process, the cement is produced when clinker, mineral additions, and gypsum are granulated finely by grinding mill. The raw meal is suspended and heated by recycled hot air in preheater.

3.2 The RDF production process and utilization in cement production

The European Commission Joint Research Center Science for Policy Report, “Best Available Techniques (BAT) Reference Document for Waste Treatment”, presents an exhaustive analysis of available technologies and current practice for handling different kinds of wastes having into account economic, social and environmental impacts (Pinasseau et al., 2018). Section 3.3 of the BAT report describes the mechanical treatment of wastes with energetic value, which includes the preparation, removal of noncombustible and part or the non-compostable organic fraction from MSW. The typical process includes operations for classification, size reduction, water evaporation, compaction and storage. Final characterization of the produced RDF is mainly dependent on the final user requirements, such as heating value, ash content, water content, volatile matter, biomass composition and elemental composition. All the processes involved in RDF production generate air and water emissions, as well as consumption of water and energy. The principal users of RDF produced in the European Union are cement production and energy production installations. Possible feeding points for RDF to the cement production process are the main burner, the rotary kiln inlet or, a feeding hopper or independent burner in the precalciner. Issues commonly encountered in the utilization of RDF include chute jamming, oversized RDF, and composition and humidity variations.

3.3 LCA goal and scope definition

The proposed study aims to evaluate and quantify potential environmental impacts for two scenarios of cement production from cradle (raw materials acquisition) to gate (cement production from clinker and additives): the current process which utilizes exclusively coal for kiln operation and electrical energy production through an annex cogeneration process (scenario 100 % coal), and an alternative scenario in which an equivalent amount of RDF in terms of heating value is used to substitute 20 wt.% coal (scenario 20 wt.% coal substitution). The functional unit was established as the production of 1 ton of cement, similar to other LCA studies for cement production and RDF utilization available in literature (Li et al., 2015; Pitre et al., 2024).

A hypothetical plant of cement production based on a dry process, located in the municipality of Yumbo, Valle del Cauca, was proposed for this study. In addition, it is assumed the plant is located next to the limestone mining operation and conditioning, which eliminates the requirement of transportation. Although the proposed process is not based or is affiliated to any of the existing cement production plants located in the region, it is valid to consider relevant aspects of their operation to validate the proposed model. One of the plants is in the urban area of the municipality of Yumbo and has a limestone mining operation for its process in the rural area of Yumbo. Limestone is quarried, crushed and mixed with water to prepare a paste, which is transported to the plant by means of a duct. Therefore, the production process is wet. Only a few installations in the world still use a wet process, due to the extra energy required to evaporate water in the cement kiln. Another installation is in the rural area of San Marcos in Yumbo, it is a dry process and it is located next to the limestone mining operation, therefore no transport it is involved. Both processes use coal which is not produced in the region.

An RDF production process from MSW provides the RDF for the scenario with 20 wt.% coal substitution. Since no information was easily accessible through literature search of the existence of such a process in the region or the RDF characteristics, it was assumed the process was located next to a MSW transfer station in the industrial zone of Arroyohondo, adjacent to the city of Cali, which is not only in the way of the location of the hypothetical process but also on the way to the location of the sanitary landfill that serves the city of Cali in the municipality of Yotoco. The proposed RDF production process consists of activities of classification, pretreatment and size reduction.

3.4 Data collection and life cycle inventory calculations

Life cycle inventories for both scenarios were based on information available in literature as discussed next.

3.4.1 Scenario 1 - Cement production with 100 % coal as fossil fuel

Li et al. (2015) carried out the LCA for cement Portland production in China with a functional unit of 1 ton of cement and reported LCI results, which were taken for this study. Inventory data were based on on-site measurements, calculation by coefficients estimated from expertise, and derivation by the mass and heat balance principle. Data corresponds to the average of 18 cement plants, including 30 production lines.

In addition, particle matter emissions are controlled by means of bag filters and electrostatic precipitators. Coal heating value was reported as 29306 kJ/kg. SO2 and NOx emissions depended on multiple factors such as the origin and composition of coal as well as the pollution control system employed. Particulate matter emissions have into account those generated due to fugitive emissions in solids transport systems, silos, calciner, mills, kiln and grate cooler systems. To calculate emissions from cogeneration Li et al., (2015) also reported emission factors which were used in this study to estimate emissions which were added to those for the cement production process.

3.4.2 Scenario 2 - Cement production with 20 wt.% coal substitution for RDF

Difference in emissions for scenario 2 have into account the reduction of carbon dioxide generated in the coal combustion in the kiln and the consideration of emissions associated with the RDF production process, an activity that occurs outside the cement production process, and the emissions generated due to the combustion of RDF in the kiln, which depend on the RDF composition. These emissions are addressed next.

3.4.3 RDF production process emissions, water and energy consumption

Pinasseau, Zerger, Roth, Canova and Roudier (2018) reported air and water emissions as well as water and energy consumption for plants that carry out mechanical treatment of MSW with calorific value, based on the information reported for 18 installations in the European Union which agreed to information exchange. Typical control systems in these plants included particulate matter with bag filters and odor control with activated carbon adsorption. An average MSW treatment capacity was estimated based on the reported information to be 480 tons of residue per day. To calculate air emissions an air flow rate for all the plants was taken as the middle value of the reported range as 57500 Nm3/h. In a similar manner, emissions are reported as a range and corresponding values for emission estimation were taken as the middle value of the range. Water emissions were also calculated from the reported range for volumetric flowrates in m3/h and emissions in mg/l. Although the mechanical treatment is a dry process, water is used for cleaning, gas scrubbing and aspersion to control dust. From the reported range for water usage reported, the middle value of 399 liters per kilogram of MSW treated was taken for this study. Energy consumption as electricity required for mechanical treatment involved in RDF production, such as cutting, grinding and classification was reported as an average value of 43 kWh per ton on MSW treated (Pinasseau et al., 2018). With these figures and the average plant capacity the emissions generated per kilogram of MSW treated are estimated. While inventory data for the RDF production process were sourced from European facilities (Pinasseau et al., 2018), the electrical grid mix was adjusted in the LCA software to reflect the Colombian energy matrix, which is characterized by a high share of hydropower (~80%). This adjustment is crucial as it significantly lowers the carbon intensity of the electricity-dependent stages compared to the coal-dominant European grid.

3.4.5 RDF yield from MSW

To calculate the corresponding emissions generated per kilogram of RDF produced, it is required to define the yield that can be obtained from MSW, which depends on the waste composition, the fractions removed due to its recyclability or putrescible characteristics as well as the final humidity. As was indicated in Table 1, RDF yield depends on the characteristics of the MSW but also in the partial or total removal of the non-compostable organic fractions, which includes mainly non-recyclable plastics, wastes of wood, rubber, leather, paper and Tetrapak, as well as vegetable and food preparation wastes, with yields around 20 % with complete removal and as high as 84 % without removing it (Salaripoor et al., 2025). The removal of such fraction improves quality and calorific value of RDF and eliminates a water evaporation step, making the process simpler and efficient. However, RDF yield is considerably low and the expected resulting emissions from burning the RDF do not benefit from the carbon neutrality of CO_2 emissions associated with burning of biomass wastes, making it less favorable from an environmental standpoint. Considering the non-compostable organic fraction removal decreases the potential benefits of CO_2 biogenic emissions, which are considered to have a GWP=0, in this study it is assumed a 50 % yield of RDF from MSW, which accounts for a partial removal of the organic non compostable fraction. The heating value for RDF of 20.5 MJ/Kg with a 50.1 % RDF yield reported by Dong & Lee, (2009) was used in this study. While RDF composition varies globally, the values from Salaripoor et al. (2025) were selected in this study as a proxy due to the similarities in MSW management in emerging economies, where high organic fractions and moisture content are prevalent.

3.4.6 Emissions resulting from RDF combustion in cement kiln

Emissions resulting from RDF combustion in the cement production process are estimated based on the global warming potential and other emission factors for each of the fractions comprising the RDF. Whereas it is common practice to consider emissions for biomass fractions as Carbon-neutral, other fractions such as plastics, waste tires, leather and rubber have GWP higher than zero due to its nonrenewable petrochemical origin, which need to be taken into account. For example, Salaripoor et al., (2025) estimated global warming potentials for RDF obtained from MSW in Teheran and obtained a GWP= 2.2 for RDF without compostable organic and 0.586 for RDF with compostable organic. Yet, in their work it was considered wood and paper had GWP different from zero. In this work, MSW fractions composition as well as GWP and emission factors for other contaminants such as NO_x, SO_2, CO and PM10 are taken from Salaripoor et al., (2025). However, resulting GWP for RDF produced was recalculated in this work with the consideration of GWP for wood and paper as zero, due to its renewable origin, with a resulting RDF GWP of 0.36 kg CO2eq/kg RDF. All the other emission factors were left unchanged.

3.5 Impact assessment and interpretation

OpenLCA free software was used for model construction, analysis and interpretation with the free database Agribalyse 3.0.1. Recipe 2016 Midpoint H, a midpoint characterization method, was selected for impact assessment. In OpenLCA flows and process are interconnected to recreate the main production process. A subprocess for RDF production process, based on emissions for RDF production, energy and water consumption was created as a new process with a functional unit of 1 kg of RDF produced from 2 kg of MSW. This process along with raw materials flows, energy consumption and emissions for cement production are used for scenario 2.

4. Results and discussion

4.1 LCI results

Table 2 summarizes the LCI inventory results for cement production with 100 % coal as reported in Li et al., (2015), as well as the corresponding proxy selected from Agribalyse database to represent the flow to the process. Inlet coal mass flow, CO2 and other contaminants emissions are indicated separately for kiln combustion (KC), power generation (A) and limestone decomposition (LD).

Table 2.
LCI inventory results for cement production with 100 % coal (Li et al., 2015)

	kg/ton cement	Proxy selected from Agribalyse
Intel		
Coal (KC+A)	85+11	Hard coal {RoW}| market for | Cut-off, S - Copied from Ecoinvent
Limestone	1150	Limestone, crushed, washed {RoW}| market for limestone, crushed, washed | Cut-off, S - Copied from Ecoinvent
Sandstone	41	Silica sand {GLO}| market for | Cut-off, S - Copied from Ecoinvent
Ferrous tailings	17.5	Iron waste
Gypsum	40	Gypsum, mineral {GLO}| market for | Cut-off, S - Copied from Ecoinvent
Outlet		
Cement	1000	Generated product flow
CO2 (LD+KC+A)	510+240+47.8= 797.8	Carbon dioxide, fossil
CO (A)	0.007	Carbon monoxide, fossil
Particulate matter (MP) (KC+A)	0.065+0.0094	Particulates, < 10 um
SO2 (KC+A)	0.094+0.0418	Sulfur dioxide
NOx (KC+A)	1.6+0.15452	Nitrogen oxides
CH4 (A)	0.004632	Methane

Note: The authors

In Table 2 can be observed CO2 emissions are higher for LD (510 kg/ton) than for KC (240 kg/ton). Therefore, the potential reduction of CO2 emissions that can be achieved by substitution of fossil fuel for RDF is limited, requiring considerably higher than 20 % substitution rates for a greater impact (Zhang & Mabee, 2016), whereas more significant reductions could be obtained by clinker ratio reduction in the cement. Emissions from PM, SO2 and NOx are generated in the coal combustion in the kiln and power generation process.

Table 3 summarizes the estimated LCI inventory results for cement production with 20 wt.% coal substitution for RDF, based on the results reported by Li et al. (2015) and Salaripoor et al. (2025) as well as the corresponding proxy selected from Agribalyse database to represent the flow to the process. 20 wt.% of coal substitution corresponds to a mass of 17 kg, which represents a heating value of 498236 kJ (29308 kJ/kg coal). Reported Heating value for RDF is 20500 kJ/kg (Dong & Lee, 2009). Therefore, a mass of 24.3 kg of RDF is required. With this mass of RDF, emissions from RDF combustion are calculated with the emission factor estimated in this study for CO2 (0.346 KgCO2/kg) and those reported in literature (Salaripoor et al., 2025). In addition, RDF produced needs to be transported to the location of the cement plant. For the calculation it is assumed the transfer station of MSW from the city of Cali is located in the industrial zone of Arroyohondo, which is the most convenient location as is next to the city and in the way to the industrial zone of San Marcos, where the hypothetical plant is located, correspondent to a distance of 21.5 km according to google maps. To introduce the transport proxy to OpenLCA it is necessary to establish the type of vehicle and its Euro emission standard. In the present study it is assumed lorry transport with a capacity of 16-32 metric tons and Euro 3. By multiplying the RDF mass required and the distance a transport flow of 522.45 kg*km is obtained.

Table 3.
LCI inventory results for cement production with 20 wt. % coal substitution

	kg/ton cement	Proxy selected from Agribalyse
Inlet		
Coal	68+11	Hard coal {RoW}| market for | Cut-off, S - Copied from Ecoinvent
Limestone	1150	Limestone, crushed, washed {RoW}| market for limestone, crushed, washed | Cut-off, S - Copied from Ecoinvent
Sandstone	41	Silica sand {GLO}| market for | Cut-off, S - Copied from Ecoinvent
Ferrous tailings	17.5	Iron waste
Gypsum	40	Gypsum, mineral {GLO}| market for | Cut-off, S - Copied from Ecoinvent
CDR	24.3	Flujo de producto subproceso CDR
RDF transport (kg*km)	522.45	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Cut-off, S - Copied from Ecoinvent
Outlet		
Cement	1000	Generated product flow
CO2 (DC+CC+A+CDR)	510+192+47.8+8.75=758.5	Carbon dioxide, fossil
CO (CC+A+CDR)	0.1477	Carbon monoxide, fossil
Material particulado MP (CC+A+CDR)	0.1436	Particulates, < 10 um
SO2 (CC+A+CDR)	0.1761	Sulfur dioxide
NOx (CC+A+CDR)	1.8429	Nitrogen oxides
CH4(A)	0.004632	Methane

Note: The authors

As a result of the substitution of 17 kg of coal for 24.3 kg of CDR, CO2 emissions from coal combustion in the kiln should decrease. In Table 2 CO2 emissions due to combustion are 240 kg, which are not obtained stoichiometrically from 85 kg of coal assuming complete combustion. Therefore, a proportional 20 % decrease of CO2 emissions due to combustion was taken for the scenario with RDF substitution, which corresponds to 48 kg CO2, and a remaining CO2 emission of 192 kg. Yet, emissions also result from the

RDF production process which need to be taken into account in the cement production process. Table 4 presents the LCI inventory results estimated for RDF production process according to the available information previously discussed (Pinasseau et al., 2018). In openLCA the RDF production process is created as a subprocess which acts as provider of the RDF inlet flow to the cement production process.

Table 4.
LCI inventory results for RDF production process

	kg/kg CDR	Proxy selected from Agribalyse
Inlet CDR process		
Water (m3/ kg CDR)	0.78	Tap water {GLO}| market group for | Cut-off, S - Copied from Ecoinvent
Electricity (kWh/kg CDR)	0.086	Electricity, medium voltage {CO}| market for electricity, medium voltage | Cut-off, S - Copied from Ecoinvent
Municipal solid waste	2	Raw material generated flow
Outlet CDR process		
CDR (kg)	1	Generated product flow
Air emissions CDR proces		
HCl	0.863	Hydrochloric acid
COT	190.900	TOC – Total organic carbon
VOC	20.125	Volatile organic compounds
Cd	0.0259	Cadmium
Hg	0.0259	Mercury
As	0.0230	Arsenic
Pb	4.025	Lead
Cr		NA
Co	0.0288	Cobalt
Ni	0.0173	Nickel
Zn	0.518	Zinc
Water emissions CDR process		
DBO5	8.838	BOD5, Biological Oxygen Demand
DQO	23.844	COD, Chemical Oxygen Demand
COT	4.596	TOC – Total organic carbon
P total	1.025	Phosphorus
Cd	0.002	Cadmium
Hg	0.000	Mercury
As	0.004	Arsenic
Pb	0.004	Lead
Cr		NA
Cu	0.014	Copper
Mn	0.035	Manganese
Ni	0.002	Nickel
Zn	0.035	Zinc

Note: The authors

4.2 Impact assessment

LCI inventory results are used to create a process in OpenLCA, considering inlet flows are provided by market flows, auxiliary sub processes such as electricity and transport and natural resources, whereas outlet flows correspond to the product, waste disposal scenarios if any and emissions to air, water and soil. After creating the process, a product system is created. A product system is described by ISO 14040, (2006) as a "collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product". Last, a project is created to compare both product systems according to a selected method. In this work the method Recipe 2016 Midpoint (H) was selected for analysis.

Figure 1 presents the impact assessment results for eighteen categories available in the selected method. LCA software tools such as OpenLCA present the results for each assessed impact category in a specific method by automatically escalating the highest value obtained when evaluating several process options within a category as 100 %, and all the other choices are escalated accordingly for comparison purposes. This facilitates interpretation, as all the categories have different units and common values for different categories differ considerably. In this way, it is possible to verify which categories need the most attention instead of focusing on specific values, which cannot be contrasted to recommended values within each category (Morales & Marulanda, 2025).

Almost all of the categories assessed are considerably higher for scenario 100 % coal, with a reduction around 20 %, consistent with the decrease in fossil fuel consumption, for scenario 20 wt.% coal substitution in categories such as fossil fuel scarcity, freshwater ecotoxicity and eutrophication, human carcinogenic and non-carcinogenic toxicity, ionizing radiation, marine ecotoxicity and marine eutrophication, which are also representative of environmental aspects of importance when assessing a process. Global warming potential was 895 kg CO2eq/ton for scenario 100 % coal vs 840 for scenario 20 wt.% coal substitution, which represents a reduction of roughly 6%. As was previously pointed out, the impact of fossil fuel substitution in terms of CO2 emissions is limited due to higher emissions from limestone decomposition, which are unavoidable without substitution of raw materials (Schneider, Hoenig, Ruppert, and Rickert, 2023). At the same time, CO2 as well as other criteria contaminants emissions such CO, NOx, SO2, PM are also generated during RDF production, transport to the plant and combustion in the process due to fossil fuel consumption involved and the presence of MSW fractions derived from fossil fuels, which correspond to a reduction of roughly 5% for scenario 20 wt.% coal substitution in the category of mineral resource scarcity. A 10 % decrease in stratospheric ozone depletion category for scenario 20 wt.% coal substitution could also be associated with fossil fuel reduction whereas remaining categories are similar for both scenarios or the maximum difference is around 5 %.

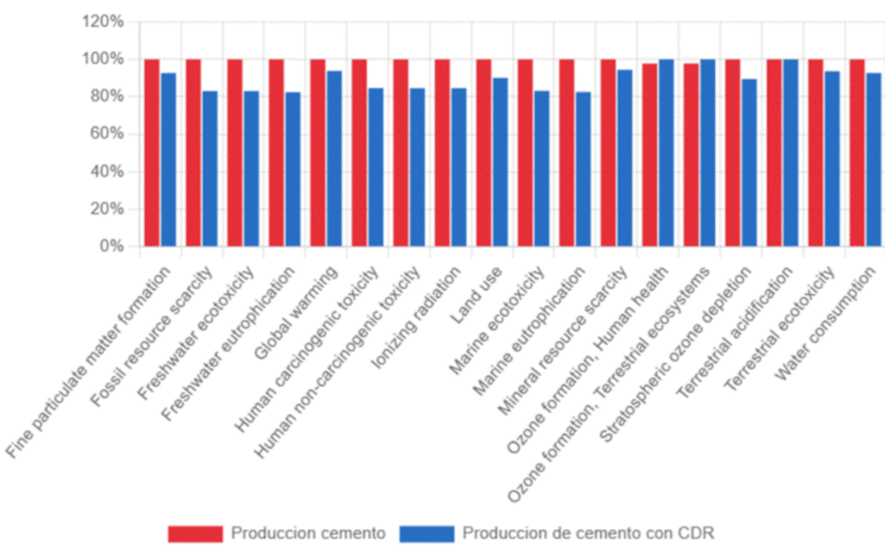

Figure 1. Impact assessment results for categories considered in method Recipe Midpoint H

Note: The authors

Figure 2 shows the top 5 contributions to global warming potential category for scenario 100 % coal. Most of CO2 emissions (798 kg) correspond to the production process, combustion, limestone decomposition and power generation, whereas contributions for coal, sandstone, silica and gypsum market flows are marginal in comparison. A similar trend is observed in all the other categories. Similar figures are obtained for scenario 20 wt.% coal substitution. As was previously discussed, a more pronounced decrease in emissions could be achieved by modifying the clinker to additives ratio in the cement, as has been shown in literature (Hossain, Poon, Lo and Cheng, 2017) as it decreases the amount of CO2 released by limestone decomposition. Although a higher substitution rate of coal could also be suggested, difficulties might arise related to operational problems such as jamming or issues related to RDF supply. Yet, RDF incorporation into cement production should not be considered only as a measure to reduce emissions. Kukreja et al., (2023) reviewed production cost, environmental impact and operational issues of several alternative fuels in cement production, and concluded the potential economic and environmental benefits are significant due to high internal rates of return, as well as a cost-effective waste management treatment option. Similar CO2 emissions reduction was reported by Pitre et al., (2024) in the life cycle analysis of the incorporation of RDF in cement production. A 7 % reduction was reported when biogenic CO2 emissions were considered carbon neutral. In a similar way Hossain et al., (2017) reported emissions reduction from 12 to 15 % when using RDF without including the organic fraction. Yet, these studies did not make any reference to emissions associated with RDF production and utilization, which is an essential step in assessing the real impact of additional activities outside the main process which might have a considerable impact on LCA results.

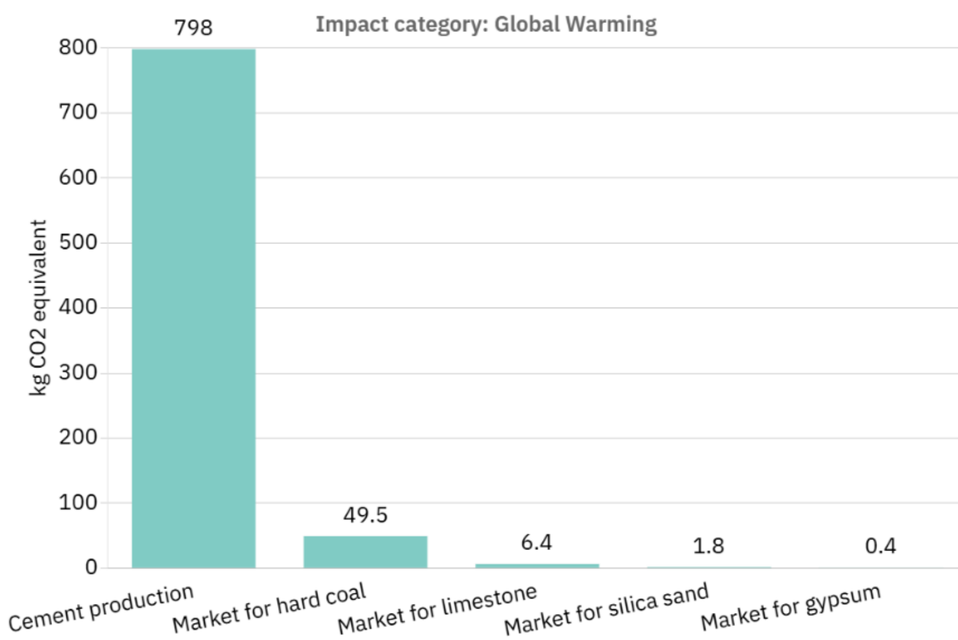

Figure 2. Top 5 contributions to global warming potential for scenario 100 % coal

Note: The authors

5. Conclusions

The cement industry has established a roadmap for reducing progressively carbon dioxide emissions by 2050. One of the alternatives considered to accomplish this goal is the incorporation of refuse-derived fuels (RDF) as a partial substitute for fossil fuels, mainly coal. In this study it was conducted a life cycle assessment (LCA) of the substitution of 20 wt.% coal for an equivalent amount of RDF in terms of calorific value in a hypothetical cement production plant located in an industrial zone of Valle del Cauca, Colombia,

in order to determine the potential reduction of emissions and environmental impact that could be achieved when compared to the process that utilizes 100 % coal. The proposed model included a hypothetical plant processing municipal solid waste from the city of Cali in an industrial zone located in the way of the location of the plant and the sanitary landfill which serves the city. Life cycle inventory results showed the main contributor to CO2 emissions is limestone decomposition rather than kiln combustion, which renders the potential impact of fossil fuel substitution limited without additional measures to reduce carbon dioxide emissions such as the clinker ratio in the cement and alternative materials. The LCA results showed a reduction of 6 % of CO2 emissions in the scenario 20 wt.% coal substitution, which was attributed to the emissions also accounted for the RDF production process, transport and combustion. Yet, additional impact categories, which are also representative of environmental aspects of importance when assessing a process, such as fossil fuel scarcity, freshwater ecotoxicity and eutrophication, human carcinogenic and non-carcinogenic toxicity, ionizing radiation, marine ecotoxicity and marine eutrophication showed a 20 % reduction when compared to the scenario 100 % coal, which was consistent with the decrease in fossil fuel consumption, indicating the partial substitution of coal for RDF could reduce impacts from the cement industry. Though greater reductions could be achieved by increasing RDF substitution percentage, public policies should be formulated to promote a more efficient waste source separation to improve the produced RDF calorific value allowing for greater percentages without altering cement kiln operation.

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Data availability

The authors declare that the article contains all the data necessary and sufficient for understanding the research.

Disclosure statement

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Disclaimer

The authors declare that the expressions, opinions, or interpretations presented in the article are their personal views and do not represent the official position of their institution

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Co-authorship

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