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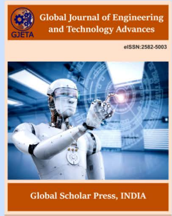

(RESEARCH ARTICLE)

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Environmental implications of concrete industry practices in Cameroon: A life cycle approach

Nimpa Giscard Desting *, Deodonne Kunwufne, Minane Jacques Rémy and Tinchie Donald

National Advanced School of Engineering, Department of Civil Engineering and Urban Planning; University of Yaoundé I – Cameroon.

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Abstract

Rapid urbanization in sub-Saharan Africa is driving a sharp increase in concrete use, raising significant environmental concerns. This study evaluates the environmental impacts of concrete production in Cameroon through a life cycle assessment (LCA), with the aim of identifying effective strategies for impact reduction. The analysis is based on primary data from 18 concrete batching plants across major urban centers, combined with national-level secondary data. It follows ISO 14040 standards and applies the IMPACT 2002+ method within SimaPro 9.0. The functional unit is 1 m^3 of ready-mix concrete. Cement production accounts for the majority of impacts, contributing over 80% of greenhouse gas emissions (347 kg CO_2-eq/m^3 out of 427 kg CO_2-eq/m^3), 57% of non-renewable energy use, and most human health effects (168 DALYs/year). Clinker content is the main driver of emissions, while electricity use and transport distances have smaller effects. Results related to human toxicity vary across impact assessment methods. By combining empirical data with regional assumptions, this study addresses a gap in LCA research for emerging economies. It highlights the need for clinker substitution, improved energy efficiency, and optimized logistics to reduce the environmental footprint of concrete.

Keywords: Concrete industry; Cameroon; Life Cycle Assessment; cement production; Carbon Footprint; building materials

1. Introduction

Concrete remains the cornerstone of modern construction, with global production surpassing 30 billion tonnes annually, making it the most consumed man-made material by volume [1]. Its extensive use in both industrialized and rapidly developing regions reflects an accelerating demand for resilient infrastructure, particularly in the face of urbanization, demographic shifts, and climate adaptation imperatives [2, 3]. However, the environmental burden of concrete production is considerable. Cement manufacturing, its most energy and emissions intensive component, is alone responsible for approximately 7–8% of global anthropogenic CO_2 emissions, largely due to the calcination of limestone and the combustion of fossil fuels during clinker production [4, 5].

The construction sector's contribution to climate change, resource depletion, and ecosystem degradation has intensified calls for sustainability-driven transformation, particularly in emerging economies where urban growth is most rapid [6, 7, 8]. Life Cycle Assessment (LCA), standardized by ISO 14040 and ISO 14044, has emerged as the principal methodological framework for evaluating environmental impacts across the entire life cycle of building materials, from raw material extraction to end-of-life management [9, 10, 11]. Yet, despite LCA's growing application in high-income contexts, its deployment in sub-Saharan Africa remains limited due to insufficient regional life cycle inventory (LCI) data and fragmented production systems [12, 13, 14].

* Corresponding author: Nimpa Giscard Desting

In the Cameroonian context, concrete production is undergoing rapid expansion driven by large-scale public infrastructure initiatives and rising housing demand [15, 16]. However, the industry is characterized by a dual structure: formal, industrial-scale batching plants with relatively advanced technologies coexist with informal, decentralized mixing practices in peri-urban and rural settings. This heterogeneity leads to inconsistent quality control, variable environmental performance, and a general lack of traceability in material flows. Compounded by an absence of reliable, geographically contextualized life cycle inventory (LCI) datasets, the environmental implications of concrete production in Cameroon remain poorly understood.

Addressing this knowledge gap is critical not only for national sustainability planning but also for contributing to global decarbonization goals within the construction sector [17]. As environmental impacts of concrete vary significantly with local energy mixes, raw material sourcing, and production technologies, context-specific LCA studies are essential for generating actionable insights [18]. Furthermore, aligning such research with advanced LCA platforms and multi-impact methods, such as IMPACT 2002+, ReCiPe, or Eco-Indicator 99, can enhance methodological rigor and support robust decision-making frameworks [19].

This study seeks to develop a comprehensive, locally calibrated Life Cycle Assessment of concrete production in Cameroon. By leveraging empirical field data, stakeholder engagement, and advanced modeling techniques, it aims to identify critical environmental hotspots, examine the implications of technological and logistical choices, and inform pathways toward low-carbon, resource-efficient construction practices in the region.

2. Methodological framework of the LCA

2.1. Brief overview of the concrete industry in Cameroon

This section provides a detailed overview of the concrete industry in Cameroon, with a focus on the sourcing and processing of raw materials as well as the production methods commonly employed across the country. Particular attention is given to the technological infrastructure, production systems, and key organizational actors shaping the sector.

2.1.1. Mapping the concrete production sector in Cameroon

A survey identified 18 operational concrete batching plants across multiple regions, including urban centers like Yaounde, Douala, Bafoussam, Garoua, and Maroua. To illustrate the industrial landscape, Table 1 presents a summary of the main concrete production companies identified during field investigations, including their geographic distribution and operational status.

Table 1 Concrete batching plants identified in Cameroon

N°	Identified concrete batching plants	Geographic distribution	Operational status
1	Cimencam	Centre - Yaounde	Operational – Under construction
2	KT&CO	Centre - Yaounde	Operational – Fixed plant
3	Cameroun Concentre Company Sarl (CMCC)	Centre - Yaounde	Operational – Fixed plant
4	Béton Construction et Carrière (BCC)	Centre - Yaounde	Operational – Fixed plant
5	Djemo BTP	Centre - Yaounde	Operational – Under construction
6	Alpha Beton	Centre - Obala	Operational – Fixed plant
7	Razel Cameroun	Centre - NTUI	Operational – Fixed plant
8	Cimencam	Littoral - Douala	Operational – Under construction
9	Goker	Littoral - Douala	Operational – Fixed plant
10	Les *Bâtisseurs Réunis*	Littoral - Douala	Operational – Fixed plant
11	Besix Cameroun Sarl	Littoral - Douala	Operational – Under construction
12	Béton Construction et Carrière (BCC)	Littoral - Douala	Operational – Fixed plant

13	Cameroon Concrete Company (CCC)	Littoral - Dibamba	Operational – Fixed plant
14	Kalfrelec	Littoral - Dibamba	Operational – Fixed & Mobile plant
15	CIMAF	Ouest - Bafoussam	Operational – Fixed plant
16	CIMAF	Nord - Garoua	Operational – Fixed plant
17	CIMAF	Extrême Nord - Maroua	Operational – Fixed plant
18	Dangote	Est - Bertoua	Operational – Fixed plant

2.1.2. Locally applied concrete manufacturing technologies

Field investigations revealed that local concrete production methods differ slightly across facilities, depending on their equipment and operational practices. These plants are broadly categorized into fixed and mobile types, with all surveyed facilities being fixed installations—except for Kalfrelec, which also operates a mobile unit.

Fixed batching plants generally include a cement silo with filtration, aggregate storage and dosing systems, weighing equipment, a water supply unit, and a concrete mixer. Most plants utilize modern, sealed mixers to comply with environmental standards, enhancing both product quality and emission control.

2.1.3. Local production process

The concrete production process observed at the surveyed plants follows standardized stages:

- Material dosing: Cement, aggregates, water, and admixtures are measured based on predefined mix designs;
- Mixing: The ingredients are homogenized in high-efficiency mixers, either in dry or wet form;
- Quality control: Regular sampling is performed to test properties such as compressive strength, water content, and consistency;
- Delivery: The ready-mix concrete is transported to construction sites using rotating drum trucks to prevent material segregation.

Mobile batching plants follow a similar production logic but offer greater logistical flexibility, particularly for remote or temporary construction sites. Their use is increasing in response to infrastructure development in less accessible regions.

In addition to industrial-scale production, concrete is also frequently prepared on-site by individual workers or small-scale contractors. In such cases, raw materials are manually dosed and mixed directly at the construction site using basic equipment, such as small drum mixers or, occasionally, manual tools. While this informal approach is widely practiced for small to medium-scale projects, it often lacks rigorous quality control and adherence to environmental standards.

2.2. Concrete industry LCA in Cameroon

2.2.1. Objectives and Scope of the Study

This study assesses the environmental impact of Cameroon's concrete industry using a life cycle assessment (LCA) approach, with the aim of identifying key impact sources and informing more sustainable construction practices. As concrete production expands across sub-Saharan Africa due to rapid urbanization, Cameroon faces growing environmental challenges linked to raw material extraction, processing, and transport, particularly across diverse and informal production systems.

The functional unit selected is 1 m^3 of ready-mix concrete, a standard reference commonly used in LCA studies to evaluate environmental impacts in relation to structural performance [20, 21, 22].

System boundaries were defined based on field data, encompassing raw material extraction, processing, transport, concrete production, and delivery to construction sites. Key inputs include cement, aggregates, water, and admixtures. Transport over long distances and variable infrastructure contributes significantly to fuel consumption and emissions. Concrete mixing involves controlled dosing to ensure structural performance, while time-sensitive delivery under local climatic conditions adds further environmental pressure. The system is modeled following ISO 14040, distinguishing input and output flows across each elementary process.

This research highlights the need for regionalized LCA approaches in areas with distinct production practices. Given that cement activities contribute to over 8% of global CO_2 emissions [20], the findings could inform national strategies to reduce the environmental impact of the construction sector in Cameroon and similar regions.

2.2.2. Life Cycle Inventory Approach

The inventory modeling drew on multiple sources: primary data from site visits, secondary data from relevant literature, and context-specific assumptions based on national practices. Concrete production volumes were estimated from the average daily outputs reported by the surveyed plants, as presented in Table 2.

Table 2 Daily production of the surveyed concrete plants

Concrete plants	Proposed formulation ranges	Compressive strength (MPa)	Typical use cases	Average daily quantities (m^3)
Béton Construction et Carrières (BCC)	B12 / B40	12 to 40	Small foundations, non-structural works, all structural uses up to special structures	328
Razel – BEC, Douala				200
Razel – BEC, Mfou				190
Cameroon Concentre Company				230
Les *Bâtisseurs Réunis*	B15 / B35	15 to 35	Foundations, slabs, beams, standard columns, multi-story buildings	275
Kalfrelec				164
Goker				180
KT&CO				160
Cameroon Concrete Company (CCC)	B20 / B40	20 to 40	From Slabs, beams, to bridges	190
Under Construction[a]	B15 / B30	15 to 30	Foundations, slabs, beams, columns	825
Not Visited[b]				950
Total	3,692			

[a] Plants under construction and nearly operational as observed during field visits. Three in particular, whose production is estimated based on that of Les *Bâtisseurs Réunis*, given their strong technological profile similarity. [b] This group includes the three CIMAF plants (West, North, Far North), the DANGOTE plant in the East, and Alpha Béton in Obala, which were not accessible. Their production is estimated based on that of Cameroon Concrete Company.

The proportions of aggregates, water, and admixtures used in the mixes were determined from formulation data provided by these facilities, which are detailed in Table 3.

Table 3 Mix proportions formulated by the concrete plants visited

Concrete plant	Mix Composition per Unit Volume (Kg/m^3)											
	Mix 1				Mix 2				Mix 3			
	Cement	FA	CA	Water	Cement	FA	CA	Water	Cement	FA	CA	Water
Les *Bâtisseurs Réunis*	200	800	1140	180	350	720	1180	180	450	735	1200	180
Kalfrelec	200	800	1140	170	350	725	1180	170	400	730	1200	170
Cameroun Concrete Company (CCC)	300	705	1166	180	350	720	1103	180	450	735	1135	180
KT&CO	250	700	1160	180	350	720	1100	180	450	735	1135	180
Béton Construction et Carrières (BCC)	300	705	1166	180	350	720	1103	180	450	735	1135	180

Goker	200	700	1140	175	350	720	1170	175	450	735	1200	175
Razel – BEC, Douala	300	750	1175	180	350	720	1190	180	450	735	1200	180
Razel – BEC, Mfou	300	750	1175	180	350	720	1190	180	450	735	1200	180
Cameroun Concentre Company (CMCC)	300	705	1166	180	350	720	1103	180	450	735	1135	180

FA = Fine Aggregates CA = Coarse Aggregates Further specifications regarding the types and dosages of admixtures are outlined in Table 4.

Table 4 Admixture proportion added per unit volume in the surveyed concrete plants

Concrete plant	Type of admixtures used and quantity per unit volume (l/m^3)											
	Plasticizer			Superplasticizer			Retarder			Accelerator		
	Mix			Mix			Mix			Mix		
	1	2	3	1	2	3	1	2	3	1	2	3
Les *Bâtisseurs Réunis*	4	4	4	4	4	4	4	4	4	4	4	4
Kalfrelec	4	4	4	4	4	4	4	4	4	4	4	4
Cameroun Concrete Company (CCC)	0	0	0	1,78	1,90	3	0	0	0	0	0	0
KT&CO	4	4	4	4	4	4	4	4	4	4	4	4
Béton Construction et Carrières (BCC)	4	4	4	4	4	4	4	4	4	4	4	4
Goker	3	3	3	3	3	3	3	3	3	3	3	3
Razel – BEC, Douala	4	4	4	4	4	4	4	4	4	4	4	4
Razel – BEC, Mfou	4	4	4	4	4	4	4	4	4	4	4	4
Cameroun Concentre Company (CMCC)	4	4	4	4	4	4	4	4	4	4	4	4

Finally, transport distances from raw material sources to concrete plants were measured, with variations linked to resource distribution and infrastructure availability, as shown in Table 5.

Table 5 Supply distances for cement, aggregates, and admixtures

Concrete plants	Supply distances (Km)			
	Cement (Km)	Fine Aggregates (Km)	Coarse Aggregates (Km)	Admixtures (Km)
Les *Bâtisseurs Réunis*	20	70	70	30
Kalfrelec	30	60	40	30
Cameroun Concrete Company (CCC)	20	50	40	25
KT&CO	10	10	10	10
Béton Construction et Carrières (BCC)	35	15	15	5
Goker	10	60	25	15
Razel – BEC, Douala	25	65	60	25
Razel – BEC, Mfou	50	5	5	25
Cameroun Concentre Company (CMCC)	25	5	5	5
Average distances (Km)	25	40	40	25

In cases where primary data were unavailable, reasonable assumptions were made to fill gaps and streamline the analysis. Specifically, this study assumes a constant population growth rate of 2.64% annually from 2021 to 2023, with an average household size of four. The proportion of new housing built with permanent materials (49.8% in 2014) is assumed to remain unchanged [23]. Concrete batching plants are assumed to be supplied by local water utilities, and among new constructions using site-mixed concrete, 25% are two-story building and 75% are single-story. Concrete is dosed at 350 kg/m^3.

The study focuses on small-scale residential construction, excluding large-scale projects. With a projected population of 28.6 million in 2023, this results in approximately 189,000 new households. By applying these assumptions and considering the growth of the middle class, concrete demand estimates are derived, as presented in Tables 6 and Table 7.

Table 6 Concrete structural elements and volumes for the single-story model

Structural elements	Description	Number and dimensions of concrete elements	Required concrete volume (m^3)
Foundation	Continuous strip footing, 15 cm thick and 20 cm high	Footing cast along: 2×13.88 m + 2×7.89 m and 3×7.89 m + 2×5.2 m	2.32
Columns	Columns with a height of 2.8 m	16 columns, cross-section: 15×15 cm	1.008
Tie beam (reinforced concrete ring beam)	Tie beam along load-bearing walls, 15×15 cm	Tie beam cast along: 2×13.88 m + 2×7.89 m and 3×7.89 m + 2×5.2 m	1.74
Septic tank slabs[1]	Upper and lower slabs, 15 cm thick, for 3 septic tank chambers	Slabs over 2×2 m×3 m	1.8
Total	6.868		

[1] The local sanitation system used is an individual on-site treatment system, consisting of three septic tank chambers and a soakaway pit.

Table 6 presents the estimation for the usable concrete volume required for the construction of structural elements in a single-story dwelling, which is calculated to be 6.868 m^3. Based on the assumptions made, the total volume required is accordingly calculated as:

$$Vt_1 = 189,073 \times 49.8\% \times 6.868 \times 75\% = 485,009.68 \text{ m}^3.$$

Moreover, Table 7 shows the estimation for the usable concrete volume required for the structural elements of a two-story dwelling.

Table 7 Concrete elements specification and volume for two-story Model

Structural elements	Description	Number and dimensions of concrete elements	Required concrete volume (m^3)
Foundation	Isolated footings, 15 cm thick	20 footings, each: 0.15 m × 0.45 m × 0.6 m	0.81
Ground floor columns	Columns with a height of 3.8 m (up to footing)	24 columns, cross-section: 15 × 15 cm	2.052
Tie beam (reinforced concrete ring beam)	Tie beam along load-bearing walls, 15 × 15 cm	Total length: 80.86 m × 0.15 × 0.15 m	1.16
First floor columns	Columns with a height of 2.8 m	26 columns, cross-section: 15 × 15 cm	1.638
Staircases	Casting of 2 ramps and steps	Dimensions: 2 × 1.175 m × 0.15 m × 7 m	2.4675
Septic tank slabs[1]	Upper and lower slabs, 15 cm thick, for 3 septic tank chambers	Slabs over 2 × 2 m × 3 m	1.8
Total	9.9275		

The locally used sanitation system is an individual on-site system consisting of three septic tank chambers and a soakaway pit.

This volume is estimated at 9.9275 m^3. Based on the adopted assumptions, the total concrete volume is calculated as follows:

$$Vt_2 = 189{,}073 \times 49.8\% \times 9.9275 \times 25\% = 233{,}689.26 \text{ m}^3$$

By integrating empirical data with context-specific assumptions, this life cycle inventory offers a realistic representation of concrete production in Cameroon and helps bridge a crucial gap in regional LCA data availability. Similar approaches are recommended by global frameworks such as ISO 14044 for settings lacking robust inventories [24], highlighting the value of local data collection in improving LCA accuracy in emerging economies.

Based on the total volume previously determined, the quantities of raw materials required per functional unit (FU), as well as the corresponding annual totals, are presented in Table 8.

Table 8 Annual total quantities of raw materials

Material	Process	Quantity per FU (t)	Annual total (t)
Cement	Extraction	0.35	656,003.229
Fine Aggregates	Extraction	0.72	1,349,492.357
Coarse Aggregates	Extraction	1.15	2,155,439.181
Water	Extraction	0.18	337,373.089
Additives	Extraction	0.016	29,988.720

The life cycle inventory (LCI) was established using data collected from key industry stakeholders, along with calculations informed by earlier assumptions. In addition to these, several methodological considerations were integrated into the process. First, for raw material extraction, input-output data for cement production were drawn from a scientific study conducted in Zimbabwe [25] and from Petek et al. [26]. Data related to the extraction and use of chemical additives were taken from Petek [27]. Second, the inventory data related to water extraction and distribution were sourced from a model developed by a local utility in South Africa and incorporated into the SimaPro software. Third, transport-related emissions were estimated based on average fuel consumption, assumed to be 35 liters per 100 kilometers, according to field interviews with drivers. Additionally, it was considered that engine oil levels decrease by approximately 2 liters every 100 km.

Transportation modes were differentiated based on material type: semi-trailers (44 tonnes) were used for cement, 28-tonne trucks for aggregates and additives, and 15 m^3 mixer trucks for ready-mixed concrete. An average transport distance of 50 km was assumed across all materials.

Once consolidated, these data enabled the development of a normalized inventory per functional unit, which serves as the basis for emission calculations in the Cameroonian concrete industry, as presented in Table 9.

Table 9 Activity data per FU for emissions in Cameroonian concrete industry

Life cycle stage	Unit	Value	Life cycle stage	Unit	Value
Raw material extraction and production			Raw material transportation		
Cement production			Cement transport		
Input			*Diesel*	*kg*	*0.0585*
Clinker	*kg*	*315.875*	*Lubricant*	*kg*	*0.0036*
Gypsum	*kg*	*16.625*	Aggregate transport		
Electricity	*kWh*	*13.16*	*Diesel*	*kg*	*0.785*
Output			*Lubricant*	*kg*	*0.048*
Cement	*kg*	*350*	Admixture transport		

Aggregate production			*Diesel*	*kg*	*0.0042*
Input			*Lubricant*	*kg*	*0.00024*
Diesel	*kg*	*1.762*	Concrete production		
Output			Input:		
Fine Aggregates	*kg*	*720*	*Cement*	*kg*	*350*
Coarse Aggregates	*kg*	*1150*	*Fine Aggregates*	*kg*	*720*
Admixture Production			*Coarse Aggregates*	*kg*	*1150*
Input			*Admixtures*	*kg*	*16*
Electricity	*kWh*	*5.28*	*Water*	*kg*	*180*
Output			*Electricity*	*kWh*	*3.059*
Plasticizer	*kg*	*4*	Output		
Superplasticizer	*kg*	*4*	*Concrete*	m^3	*1*
Retarder	*kg*	*4*	Concrete transportation		
Accelerator	*kg*	*4*	*Diesel*	*kg*	*0.604*
Solid Waste	*kg*	*0.008*	*Lubricant*	*kg*	*0.015*

2.2.3. Life cycle impact assessment (LCIA) methodology

The Life Cycle Impact Assessment (LCIA) was carried out using SimaPro 9.0 software, implementing the IMPACT 2002+ method. This integrated approach combines mid-point and end-point modeling, enabling the characterization and damage assessment of various environmental impact categories associated with concrete production processes.

Characterization was performed by applying the mid-point factors embedded in IMPACT 2002+ to the inventory data compiled in the previous phase. This step covered fifteen mid-point categories, including but not limited to human toxicity (carcinogenic and non-carcinogenic), respiratory effects, ionizing radiation, aquatic and terrestrial ecotoxicity, ozone layer depletion, acidification, eutrophication, land occupation, climate change, and resource depletion.

Damage assessment was subsequently performed by aggregating midpoint scores into four main damage categories: human health, ecosystem quality, climate change, and resource availability. This was achieved using the damage factors defined by Jolliet et al. [28] and Baidai [29].

To evaluate the robustness of the selected impact assessment method, a sensitivity analysis was carried out. This involved comparing the results obtained using IMPACT 2002+ with those derived from the Eco-Indicator 99 (H) method. The comparison focused on the relative contributions of each life cycle stage to the various impact categories, allowing for an assessment of methodological consistency and reliability.

All characterization and damage modeling steps followed standardized LCIA procedures and employed default methodological parameters provided by SimaPro, unless stated otherwise

3. Results and discussion

3.1. Characterization and damage scores of concrete production in Cameroon

Based on the inventory data provided in the previous section, the calculation of environmental impact categories was carried out using the SimaPro software, applying the integrated impact assessment methodology, Impact 2002+. Table 10 reports the mid-point characterization scores across all life cycle stages.

Subsequently, by applying the characterization factors detailed in Table 10 to these scores, the damage scores corresponding to the various mid-point impact categories were derived, as presented in Table 11.

3.2. Sensitivity analysis

The sensitivity analyses presented here focus on verifying the robustness of the IMPACT 2002+ method and examining various process parameters in the study.

3.2.1. Sensitivity analysis of the assessment method

A sensitivity analysis was performed by comparing the IMPACT 2002+ method with the Eco-Indicator 99 (H) method. Table 12 shows the percentage contribution of each life cycle phase to the various impact categories.

It was observed that only the carcinogenic human toxicity category exhibits inconsistencies across the different phases of the process. A reversal of trends is noted in this category. According to the IMPACT 2002+ method, the phase of adjuvant production has the highest harmful influence, estimated at 59%, followed by the cement production phase at 39.9%, while water production is the least harmful, contributing only 0.2%. In contrast, in the Eco-Indicator 99 method, the cement production phase has the greatest harmful impact at 72.4%, followed by the adjuvant production phase at 11.8%, and water production remains the least harmful at 0.1%.

For the other categories, the results are very similar between the two methods, and in some cases, the results are identical, such as for acidification and eutrophication.

This sensitivity analysis indicates that, overall, the modeling is robust

Table 10 Characterization scores for all life cycle phases of the concrete industry in Cameroon

Impact category	Unit	Admixture production	Water extraction and distribution	Portland cement production	Aggregate production	Raw material transport	Concrete mixing	Concrete transport	Total
Human toxicity (carcinogenic)	kg C_2H_3Cl eq	1.95	7.44×10^{-3}	1.02	5.05×10^{-2}	7.75×10^{-2}	1.42×10^{-1}	6.32×10^{-2}	3.32
Human toxicity (non-carcinogenic)	kg C_2H_3Cl eq	7.14×10^{-1}	9.59×10^{-3}	5.93	3.82×10^{-2}	3.60×10^{-1}	6.75×10^{-1}	3.01×10^{-1}	8.03
Respiratory effects (inorganics)	kg $PM_{2.5}$ eq	3.19×10^{-2}	3.08×10^{-4}	1.69×10^{-1}	1.96×10^{-2}	2.31×10^{-2}	8.44×10^{-3}	1.95×10^{-2}	2.72×10^{-1}
Ionizing radiation	Bq C-14 eq	1.21×10^{2}	9.70×10^{-1}	3.40×10^{2}	5.03	2.21×10^{1}	2.23×10^{1}	1.81×10^{1}	5.29×10^{2}
Ozone layer depletion	kg CFC-11 eq	9.50×10^{-8}	2.07×10^{-9}	1.20×10^{-6}	1.02×10^{-7}	1.71×10^{-7}	4.29×10^{-8}	1.34×10^{-7}	1.75×10^{-6}
Respiratory effects (organics)	kg C_2H_4 eq	2.70×10^{-2}	7.04×10^{-5}	4.16×10^{-2}	1.26×10^{-2}	1.79×10^{-2}	2.26×10^{-3}	1.39×10^{-2}	1.15×10^{-1}
Aquatic ecotoxicity	kg TEG eq (water)	4.41×10^{2}	4.10	1.47×10^{3}	9.54×10^{1}	6.94×10^{2}	2.48×10^{2}	5.83×10^{2}	3.53×10^{3}
Terrestrial ecotoxicity	kg TEG eq (soil)	1.66×10^{2}	1.74	1.07×10^{3}	3.14×10^{1}	6.95×10^{2}	1.43×10^{2}	5.93×10^{2}	2.70×10^{3}
Terrestrial acidification/eutrophication	kg SO_2 eq	5.87×10^{-1}	7.03×10^{-3}	4.83	4.78×10^{-1}	6.31×10^{-1}	1.76×10^{-1}	5.40×10^{-1}	7.25
Land occupation	m^2 organic arable land	2.26×10^{-1}	2.73×10^{-3}	2.54	4.35×10^{-1}	1.02	3.03×10^{-1}	8.73×10^{-1}	5.41
Aquatic acidification	kg SO_2 eq	1.80×10^{-1}	2.32×10^{-3}	1.13	6.71×10^{-2}	1.07×10^{-1}	6.03×10^{-2}	9.03×10^{-2}	1.63
Aquatic eutrophication	kg PO_4^{3-} eq	3.90×10^{-3}	5.58×10^{-5}	4.14×10^{-2}	2.11×10^{-4}	1.38×10^{-3}	1.42×10^{-3}	1.14×10^{-3}	4.95×10^{-2}
Climate change	kg CO_2 eq	3.62×10^{1}	2.47×10^{-1}	3.47×10^{2}	7.48	1.37×10^{1}	1.11×10^{1}	1.14×10^{1}	4.27×10^{2}
Non-renewable energy	MJ primary	1.11×10^{3}	3.30	2.29×10^{3}	1.09×10^{2}	2.15×10^{2}	7.35×10^{1}	1.69×10^{2}	3.97×10^{3}
Mineral extraction	MJ surplus	6.07×10^{-1}	2.51×10^{-3}	7.97	4.34×10^{-2}	1.61×10^{-1}	1.21	1.32×10^{-1}	1.01×10^{1}

Table 11 Environmental damage per life cycle stage of concrete production in Cameroon

Impact category	Unit	Admixture production	Water extraction and distribution	Portland cement production	Aggregate production	Raw material transport	Concrete mixing	Concrete rransport	Total
Human toxicity (carcinogenic)	[DALY / kg vinyl chloride]	5.47×10^{-6}	2.08×10^{-8}	2.87×10^{-6}	1.41×10^{-7}	2.17×10^{-7}	3.99×10^{-7}	1.77×10^{-7}	9.29×10^{-6}
Human toxicity (non-carcinogenic)	[DALY / kg vinyl chloride]	2.00×10^{-6}	2.68×10^{-8}	1.66×10^{-5}	1.07×10^{-7}	1.01×10^{-6}	1.89×10^{-6}	8.42×10^{-7}	2.25×10^{-5}
Respiratory effects (inorganics)	[DALY / kg $PM_{2.5}$]	2.23×10^{-5}	2.15×10^{-7}	1.18×10^{-4}	1.37×10^{-5}	1.62×10^{-5}	5.91×10^{-6}	1.37×10^{-5}	1.90×10^{-4}
Ionizing radiation	[DALY / Bq Carbon-14]	2.55×10^{-8}	2.04×10^{-10}	7.13×10^{-8}	1.06×10^{-9}	4.63×10^{-9}	4.68×10^{-9}	3.81×10^{-9}	1.11×10^{-7}
Ozone layer depletion	[DALY / kg CFC-11]	9.97×10^{-11}	2.17×10^{-12}	1.26×10^{-9}	1.07×10^{-10}	1.80×10^{-10}	4.50×10^{-11}	1.41×10^{-10}	1.83×10^{-9}
Aquatic ecotoxicity	[PDF·m^2·yr / kg triethylene glycol]	2.22×10^{-2}	2.06×10^{-4}	7.36×10^{-2}	4.79×10^{-3}	3.48×10^{-2}	1.24×10^{-2}	2.93×10^{-2}	1.77×10^{-1}
Terrestrial ecotoxicity	[PDF·m^2·yr / kg triethylene glycol]	1.31	1.38×10^{-2}	8.46	2.48×10^{-1}	5.50	1.13	4.69	21.4
Terrestrial acidification/eutrophication	[PDF·m^2·yr / kg SO_2 eq. in air]	6.11×10^{-1}	7.31×10^{-3}	5.02	4.97×10^{-1}	6.56×10^{-1}	1.83×10^{-1}	5.61×10^{-1}	7.54
Land occupation	[PDF·m^2·yr / m^2 organic arable land]	2.46×10^{-1}	2.97×10^{-3}	2.77	4.75×10^{-1}	1.12	3.30×10^{-1}	9.51×10^{-1}	5.89
Aquatic acidification*	—	—	—	—	—	—	—	—	—
Aquatic eutrophication*	—	—	—	—	—	—	—	—	—
Climate change	[kg CO_2 / kg CO_2]	3.62×10^{1}	2.47×10^{-1}	3.47×10^{2}	7.48	1.37×10^{1}	1.11×10^{1}	1.14×10^{1}	4.27×10^{2}
Non-renewable energy	[MJ primary / MJ primary] or [MJ / kg Fe eq.]	1.11×10^{3}	3.30	2.29×10^{3}	1.09×10^{2}	2.15×10^{2}	7.35×10^{1}	1.69×10^{2}	3.97×10^{3}

Mineral resource extraction	[MJ primary / MJ surplus] or [MJ / kg crude oil]	6.07×10^{-1}	2.51×10^{-3}	7.97	4.34×10^{-2}	1.61×10^{-1}	1.21	1.32×10^{-1}	1.01×10^{1}

* The IMPACT 2002+ method lacks damage factors for aquatic acidification and eutrophication, preventing damage score calculation.

Table 12 Life cycle impact contributions by stage and method (IMPACT 2002+ and Eco-Indicator 99 H)

Impact category	IMPACT 2002+							Eco-Indicator 99 (H)						
	Adjuvant production	Water extraction and distribution	Portland cement production	Aggregate production	Raw material transport	Concrete mixing	Concrete transport	Adjuvant production	Water extraction and distribution	Portland cement production	Aggregate production	Raw material transport	Concrete mixing	Concrete transport
Human toxicity (carcinogenic) *	59.0	0.2	30.9	1.5	2.2	4.3	1.8	11.8	0.1	72.4	0.4	3.4	9.1	2.8
Human toxicity (non-carcinogenic)	8.9	0.1	74.0	0.5	4.4	8.4	3.7	—	—	—	—	—	—	—
Inorganic respiratory effects +	11.8	0.1	62.4	7.2	8.3	3.1	7.1	11.0	0.1	64.6	6.3	8.1	3.0	6.9
Ionizing radiation +	23.0	0.2	64.3	1.0	4.0	4.2	3.3	22.9	0.2	64.4	1.0	4.0	4.2	3.3
Ozone layer depletion+	5.7	0.1	71.3	6.1	7.9	2.6	6.4	5.0	0.1	77.1	4.4	6.3	2.0	5.1
Organic respiratory effects +	24.4	0.1	37.6	11.4	13.7	2.0	10.8	24.9	0.1	37.5	11.3	13.6	2.1	10.7
Aquatic ecotoxicity+	12.7	0.1	42.1	2.7	19.1	7.1	16.2	12.3	0.1	53.3	1.0	9.1	16.5	7.7
Terrestrial ecotoxicity	6.2	0.1	39.8	1.2	25.6	5.3	21.9	—	—	—	—	—	—	—
Terrestrial acidification/eutrophication +	8.1	0.1	66.8	6.6	8.6	2.4	7.3	8.1	0.1	66.8	6.6	8.6	2.4	7.3
Land occupation +	4.2	0.1	47.2	8.1	18.8	5.6	16.1	3.5	0.0	40.6	25.3	14.4	3.8	12.3
Aquatic acidification	11.0	0.1	69.2	4.1	6.3	3.7	5.4	—	—	—	—	—	—	—
Aquatic eutrophication	7.9	0.1	83.9	0.4	2.6	2.9	2.2	—	—	—	—	—	—	—
Climate Change +	8.5	0.1	81.4	1.8	3.1	2.6	2.6	8.9	0.1	80.9	1.8	3.1	2.6	2.6
Non-renewable energy use	28.5	0.1	58.9	2.8	4.3	1.9	3.5	—	—	—	—	—	—	—
Mineral resource depletion +	6.0	0.0	78.8	0.4	1.5	11.9	1.3	6.0	0.0	78.8	0.4	1.5	11.9	1.3

*Impact categories with significant trend reversal between methods include: Human Toxicity (Carcinogenic). + Impact categories with similar results across both methods include. Categories marked with "—" indicate unavailable data.

3.2.2. Sensitivity analysis of process parameters

The estimation of various process parameters was conducted by varying each parameter individually while keeping others constant in order to observe changes in the overall environmental score of the process. The different values were recorded in an Excel table, allowing us to assess, within a range of 100, the influence of each parameter on the environmental burden of the process. The parameters considered were (i) transport distances, (ii) electricity consumption and (iii) clinker consumption. Table 13 presents the sensitivity values of these parameters, expressed as percentages.

Table 13 Sensitivity analysis of concrete process parameters in Cameroon (%)

Parameters	Transport distances	Electricity consumption	Clinker consumption	Other parameters
Sensitivity (%)	10	14.2	59	16.8

Clinker consumption emerges as the most influential parameter in the environmental impact of concrete production in Cameroon. In comparison, electricity use and transport distances show limited sensitivity, while other parameters play a secondary role. These results suggest that mitigation efforts should focus primarily on reducing clinker-related impacts.

3.3. Analysis and discussion of environmental impacts

The environmental impact assessment of concrete production in Cameroon reveals that the most significant impact categories include climate change, non-renewable energy depletion, eutrophication, ecotoxicity, acidification, human toxicity, and mineral extraction. These findings align with trends observed in previous life cycle assessment (LCA) studies of the concrete industry, reinforcing the relevance of these categories.

3.3.1. Climate change

The production of concrete in Cameroon results in the emission of approximately 427 kg of CO_2-equivalent per cubic meter, of which 81.3% is attributed to Portland cement production. This corresponds to 347 kg CO_2-eq/m^3 emitted solely by the cement component.

Comparable values have been reported in the literature. For instance, Serres et al. [30] estimated emissions at 444 kg CO_2-eq/m^3 for conventional ready-mix concrete, while De Schepper et al. [22] reported 325 kg CO_2-eq/m^3, and Petek et al. [26] found values around 400 kg CO_2-eq/m^3. These figures are all based on concrete mixes containing approximately 350 kg of cement per cubic meter, which supports the finding that cement production contributes between 80% and 90% of the total carbon footprint of concrete. This convergence in data highlights the significant environmental burden of cement, thereby justifying the growing body of research dedicated to reducing its carbon impact.

In this regard, Prusinski et al. [21] conducted a life cycle assessment (LCA) on concrete made with slag-blended cement. Their results show that a 50/50 mix of Portland cement and ground granulated blast-furnace slag results in emissions of 307 kg CO_2-eq/m^3, compared to 555 kg CO_2-eq/m^3 for concrete made exclusively with Portland cement. These findings demonstrate that substituting Portland cement with more eco-friendly alternatives can reduce the environmental impact of concrete production by nearly half, representing a key strategy in sustainable construction practices.

3.3.2. Energy use and resource Depletion

The overall non-renewable energy consumption is 3980.1 MJ/m^3, with cement production accounting for the largest share (57%) followed by the use of admixtures (28%). Mineral extraction contributes 10.1 MJ/m^3 to the total energy demand. These values are notably higher than those reported in studies conducted in developed countries, such as those by Serres et al. [30] and Prusinski et al. [21], likely due to disparities in technological advancements and operational efficiencies.

3.3.3. Human health impact

According to the IMPACT 2002+ methodology, human health is one of the four primary endpoint categories, alongside ecosystem quality, climate change, and resource depletion. The total human health damage associated with concrete production is quantified at 2.22×10^{-4} DALY per m^3, which translates to a loss of 416 years of life annually across the population of Cameroon. Notably, CO_2 emissions alone contribute to 168 DALYs per year, representing an average loss of approximately 5 minutes of life per individual, assuming 62% exposure to fine particulate matter as reported by Brauer et al. [31].

3.3.4. Land Use Impact

The land use associated with concrete production is largely attributable to cement manufacturing (49.95%) and transportation processes (35%). Unlike many conventional life cycle impact assessment (LCIA) methods, the IMPACT 2002+ framework enables a detailed quantification of land occupation, a category that remains underrepresented in most environmental assessments. By integrating this dimension, IMPACT 2002+ enhances the comprehensiveness of environmental evaluations, offering critical insights into spatial resource demands often overlooked in the built environment sector.

Overall, the analysis clearly demonstrates that cement production is the dominant contributor to environmental impacts across nearly all evaluated categories, including climate change, energy depletion, land use, and human health. The latter, measured in disability-adjusted life years (DALYs), emphasizes the urgency of implementing mitigation strategies, particularly regarding CO2 emissions and air pollution from both cement manufacturing and transportation activities. These results support the development of targeted interventions within Cameroon's concrete sector, with a particular emphasis on decarbonizing cement through alternative binders, improving energy efficiency across the supply chain, and reducing transport-related emissions. By addressing these priority areas, substantial environmental and public health benefits can be achieved, contributing to more sustainable construction practices in the region.

4. Conclusion

The present study offers a comprehensive life cycle assessment (LCA) of concrete production in Cameroon, integrating empirical data from field investigations with internationally recognized methodological frameworks, notably ISO 14040 and the IMPACT 2002+ model. By examining both industrial and informal production systems, the research provides a nuanced depiction of the technological, organizational, and environmental characteristics of the national concrete sector.

Key findings reveal that Portland cement production is unequivocally the dominant contributor to environmental impacts across all assessed categories, including climate change, energy and resource depletion, human toxicity, and land occupation. With emissions reaching approximately 427 kg CO_2-eq/m^3 of concrete, 81.3% of which stems from cement, this result not only aligns with global LCA benchmarks but also underscores the urgency of transitioning towards lower-carbon binders. Sensitivity analyses further highlight clinker consumption as the most environmentally consequential parameter, thus offering a clear target for mitigation strategies.

Moreover, the study underscores the limitations of existing infrastructure, material transport inefficiencies, and process variability, especially within informal and small-scale operations, exacerbating the environmental burden. The integration of locally contextualized inventory data and assumptions strengthens the reliability of the impact assessment, particularly in a region where comprehensive environmental datasets remain scarce.

Ultimately, this research contributes valuable regionalized data to the global discourse on sustainable construction, offering evidence-based recommendations for reducing the environmental footprint of concrete in sub-Saharan Africa. Policy measures should prioritize the decarbonization of cement production through the adoption of supplementary cementitious materials, investment in energy-efficient technologies, and improvements in supply chain logistics. In parallel, efforts must be directed towards formalizing quality standards within the informal sector to ensure environmental compliance and structural reliability.

The approach demonstrated herein serves as a model for future assessments in comparable developing contexts, where balancing rapid urbanization with sustainable material use remains a critical challenge. In doing so, this study provides not only a methodological template but also an actionable roadmap for advancing environmental stewardship in the concrete industry across the Global South.

Compliance with ethical standards

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No conflict of interest to be disclosed.

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