Chapter

Life Cycle Assessment of Ordinary Portland Cement (OPC) Using both Problem Oriented (Midpoint) Approach and Damage Oriented Approach (Endpoint)

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Abstract

The concern for environmental related impacts of the cement industry is fast growing in recent times. The industry is challenged with high environmental impact which spans through the entire production process. Life cycle assessment (LCA) evaluates the environmental impact of product or process throughout the cycle of production. This can be done using either or both midpoint (process-oriented) and endpoint (damage-oriented) approaches of life cycle impact assessment (LCIA). This study assessed the environmental impact of 1 kg Ordinary Portland Cement (OPC) using both approaches of LCIA. This analysis was carried out using a data modeled after the rest of the world other than China, India, Europe, US and Switzerland. The dataset was taken from Ecoinvent database incorporated in the SimaPro 9.0.49 software. The result of the analysis showed that clinker production phase produced the highest impact and CO2 is the highest pollutant emitter at both endpoint and midpoint approaches. This is responsible for global warming known to affect both human health and the ecosystem. Also, toxicity in form of emission of high copper affects the ecosystem as well as humans. In addition, high fossil resources (crude oil) are consumed and pose the possibility for scarcity.

Keywords: Ordinary Portland cement (OPC), Environmental impact, LCA, LCIA, Midpoint, End point

1. Introduction

With the continuous change in globalization, urbanization, and increase in population, people migrate from one region to another for a better quality of life. This in turn leads to increase in population in such regions. Therefore, there is need to make provisions for infrastructures that will support this increase. The construction industry provides the necessary structure and infrastructure needed for a sustainable environment. However, this sector is faced with different environmental impacts throughout its production cycle. Concrete is one of the important materials in the construction Industry. The production of concrete is required to build the global landscape and accommodate the continuous urbanization as a result of population growth. Recently, construction sector has been recorded to produce large environmental impact which is of continuous concern to the society [1–4]. Ordinary Portland Cement (OPC) is the major constituent of concrete production. Several environmental impacts such as intensive resource and energy consumption are associated with the production of cement [5–9]. This continuous increase in the environmental impacts of the cement industry at the global level is beckoning for attention because of the possible consequences that can succeed these impacts of great concern.

The OPC consists majorly of calcium silicate minerals (limestone, sand and clay) which are extracted and thereafter transferred to the manufacturing plant where they are crushed and finally pulverized into the required texture. This is preheated and eventually transferred into a large kiln of over 1400°C for further treatment to produce the clinker [2, 10]. The clinker is allowed to cool while the heat is trapped back to the preheater unit and gypsum is added to the cooled clinker to control the setting time of the OPC produced. Clinker production is the most energy consuming of all the production stages as enormous source of fuel and electricity is needed [11, 12]. As a result, cement industry is accountable for about 12-15% of industrial energy use [13–15]. Also, about 5-7% of global CO_2 emission is produced during cement production [16]. About 2.6Gt of CO_2 gas emission was recorded from production of cement in 2011, whereby the emission was from the combustion of fossil fuels and the thermal decomposition of limestone (calcination) [17, 18]. International Energy Agency's (IEA) Greenhouse Gas R&D Programme recorded that over 800 g of CO_2 is emitted for every 1000 g of cement produced [19, 20]. Approximately 1 ton of concrete is needed annually by every individual, this makes cement an essential material which requires continuous production [5, 21, 22]. There is a need to quantify the environmental impact of the global production of cement production; the consequent effect on human health, resources and the environment as a whole; and production phases that cause the impacts so that proper recommendation and mitigation strategies can be presented. Studies have shown that the clinker production phase has the highest impact and CO2 is one of the most emitted gases [1, 8, 12, 23]. Recommendation on mitigation strategies varying from partial replacement of clinker, to use of alternative fuel etc. were given. Also, incorporation of best available techniques (BAT) to the production processes were part of the recommendations given [1, 24, 25].

Life cycle assessment (LCA) is a system-oriented tool used for the evaluation and assessment of a product's or process' environmental impacts by analyzing the entire stages of a production process beginning from resource extraction ("cradle") and continues through cement production, to cement applications like concrete structures, their use, and end-of-life (grave) [26]. This brings about the other name known as "cradle to grave". LCA gives a holistic view of the entire production process. According to International Standard Organization (ISO) 14040, the four stages of LCA are represented in **Figure 1** [28, 29].

- Goal and scope describe the assessment objectives alongside with the system of the product and/or process, functional unit, target audience, system boundaries, assumptions etc. It basically defines the jurisdiction of the assumption [30]. The functional unit that will be adopted in this study is 1kilogram of cement. All dataset, analysis and interpretation will take into account this functional unit. This study aims to analyze the environmental impact of 1 kg of cement using midpoint and endpoint LCIA approaches so as to rightly quantify the level of impact and make proper recommendation. The study will be conducted from cradle to gate i.e., from extraction to the production of cement. All data or information with respect to administration in

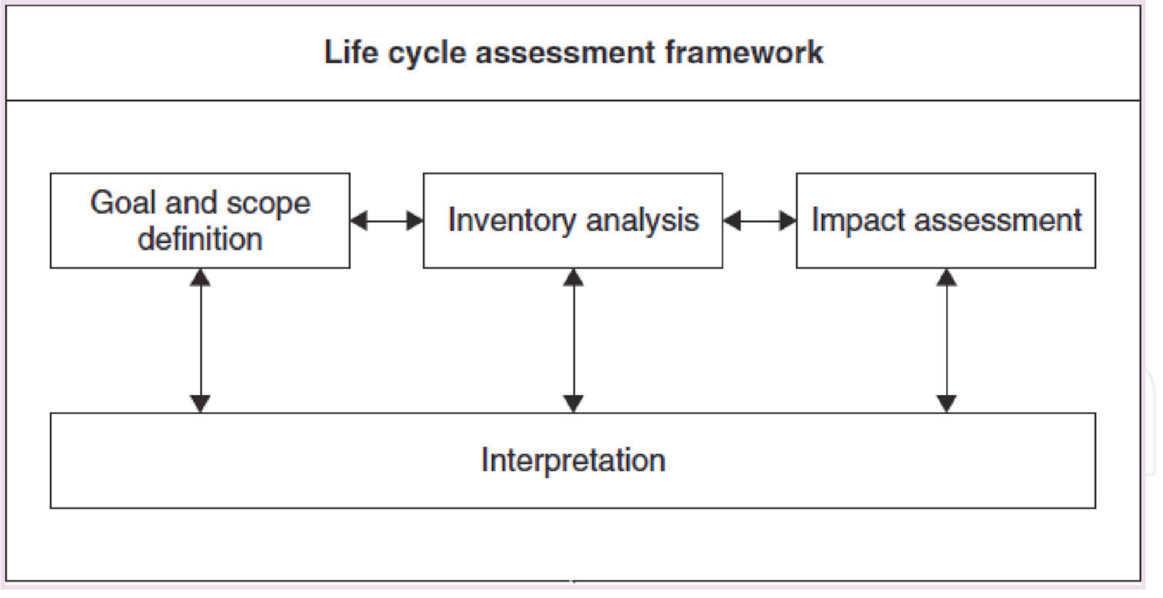

Figure 1.
Stages of LCA [27].

the plant, packaging processes and disposal will not be incorporated into the analysis.

- Life Cycle Inventory (LCI) stage has to do with the compilation of input and output inventory data that are not only consistent with the product under assessment but equally have several environmental coverages. The database of environmental impacts includes all emissions as a result of the production process. In this study, data modeled after the rest of the world apart from China, India, Europe, US and Switzerland will be considered. Dataset will be taken from Ecoinvent dataset; one of the highly recommended database company [31] which was recently considered to be one of the best database for construction materials [32].

- Life cycle impact assessment (LCIA) is a multiple-issue tool used to evaluate potential environmental impacts that are in-line with environmental resources identified in the life cycle inventory. This assessment addresses several environmental issues such as energy, climate change, water pollution, etc., thus allowing for comprehensive evaluation of the impacts of the product [27]. The LCIA stage is a multifaceted process which groups all inventory into their various impact categories, thereafter analysis is conducted at the final stage where LCIA and LCI results are interpreted.

- Interpretation which is the last stage is an efficient method used to evaluate, compute and categorize the result from the information provided by LCI and LCIA and relate them effectively by showing the effect each output data has on each impact categories and consequently establishing the goal of the study [33]. In this phase, production processes and substance with significant impacts will be presented in a comprehensive and lucid manner after which proper recommendation are made.

Several studies have been carried out with respect to life cycle assessment of the cement industry to evaluate the impact of its production processes [2, 21, 34–36].

Often times, these studies are modeled after a country, or particular cement plant in a certain place. Rarely do we find LCA study modeled after the world. Also, more studies are more focused on using the midpoint approach only. This study will therefore carry out a life cycle assessment modeled after the rest of the world other than from China, India, Europe, US and Switzerland using both endpoint and midpoint approaches to analyze the environmental impact of OPC production. The remainder of this article is divided into method under section two, results under section three, discussion under section four and the last section concludes.

2. Method

LCA is an assessment tool for analyzing the environmental implication of process or product by taking cognizance of the potential effect of the entire cycle chain of such process or product. One good posture LCA takes in a system study is to give holistic LCIA method and its calculations (environmental impacts) are based on definite factors. This helps to speed up the analysis as well as simplify the system studied.

There are two approaches in LCIA: process-oriented approach (midpoints) and damage-oriented approach (endpoints). The life cycle assessment expert can use either of them for evaluation [37]. Midpoints and endpoints are characterization models that indicate effects at different levels. In the midpoint approach, flows are categorized into environmental impacts to which they contribute. This approach contains about 18 impact categories: global warming, stratospheric ozone depletion, ionizing radiation, ozone formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity etc. [38]. This approach helps to simplify numerous flows by streamlining them into few prevalent environmental impacts. Endpoint approach on the other hand classifies impacts into 22 environmental impact categories and thereafter simplifies flow to evaluate impacts at the area of significance to life (AoSL): human health, ecosystem, resources [39]. Although, the midpoint approach gives a cause-effect evaluation right from the emission of substance or usage of resources, endpoint helps to answer the question: why should I worry about these impacts? [40].

ReCiPe, an acronym for the developers: RIVM, Radboud University, CML and PRé Consultants, is the LCIA method that will be adopted in this study; it offers the platform for carrying LCIA using both approaches [37]. The development of ReCiPe was mainly as a result of the need to harmonize the midpoint and endpoint methods and consequently break the barrier of the selection of LCIA method in LCA model [38].

When midpoint LCIA method is used for analysis, the result presents 18 impact categories, which covers several impacts while endpoint on the other hand presents the 22 impact categories. These impacts are later classified in three damage categories in the AoSL which are human health, resources and ecosystem based on their effects; giving a slightly easy result analysis. In human health category, ReCiPe uses the disability-adjusted life years (DALY) which means the years of life expended or the years of damage to life as a result of environmental impacts. Ecosystem damage category is measured by species/yr.; this denotes species lost in a year due to emissions to the environment, water body, etc. and the resources damage is based on economic loss due to marginal increase in costs as a result of scarcity emerging from resource extraction. It is measured using USD (2013) [38, 41, 42].

ReCiPe uses a cultural theory as 3 models are used to qualify 3 basic assumptions and consideration [43]. These are the Individualist (I), the Egalitarian (E) and Hierarchism (H). The Individualist (I) considers the short-range impact because of the greatest significant chemicals. Egalitarian (E) is established on preventive measure that takes into consideration the long-term perception and implied risk.

Hierarchism (H) on the other hand is a balanced perspective whose basis is on the prevalent policy principles [44]. Also, ReCiPe provides other set of weighting factors (A) by averaging the weighting factors of the three viewpoints. The balanced term H is the default, recommended choice. The average value (A) will be adopted in this study. Therefore, ReCiPe Midpoint (H)- World H and ReCiPe Endpoint (H)-World H/A, are used in this study for the assessment of ordinary Portland cement. The software used for the LCA in this study is SimaPro 9.0.49 which incorporates the latest version of Ecoinvent (v 3.5) database [45].

The dataset in **Table 1** describes the production of clinker; in the production, different types of alternative fuels and raw materials are used. This database is

Inputs from Technosphere	Amount
Ammonia, liquid	0.000918 kg
Bauxite	0.000148 kg
Calcareous marl	0.459 kg
Cement factory	6.2e-12 unit
Clay	0.326 kg
Diesel, burned in building machine	0.0132 MJ
Diesel, low-sulfur	5.61e-06 kg
Electricity, medium voltage	0.0593 kWh
Hard coal	0.0362 kg
Heavy fuel oil	0.0249 kg
Industrial machine, heavy, unspecified	3.76e-05 kg
Iron ore, crude ore, 46% Fe	0.000143 kg
Light fuel oil	0.000367 kg
Lime	0.821 kg
Hydrated, lose weight	0.00388 kg
Limestone, crushed, for mill	0.0308 kg
Liquefied petroleum gas	6.68e-07 kg
Lubricating oil	4.71e-05 kg
Meat and bone meal	0.00948 kg
Natural gas, high pressure	0.000206 m^3
Petrol, unleaded	2.54e-07 kg
Petroleum coke	0.00442 kg
Pulverized lignite	0.00167 MJ
Refractory, basic, packed	0.00019 kg
Refractory, fireclay, packed	8.21e-05 kg
Refractory, high aluminum oxide, packed	0.000137 kg
Sand	0.0103 kg
Steel, chromium steel 18/8, hot rolled	5.86e-05 kg
Tap water	0.336 kg
Urea, as N	1.5e-06 kg
Transport, freight, lorry	0.05tkm

Inputs from Technosphere, wastes	Amount
Inert waste, for final disposal	−0.000179 kg
Municipal solid waste	−4.45e-05 kg
Inputs from environment	**Amount**
Water, cooling, unspecified natural origin	9.57e-06 m3
Water, unspecified natural origin	0.0016 m3
Emissions to air	**Amount**
Acenaphthylene	2.68e-10 kg
Ammonia	2.25e-05 kg
Antimony	2.24e-09 kg
Arsenic	1.22e-08 kg
Benz(a)anthracene	5.18e-12 kg
Benzene, hexachloro-	2.59e-12 kg
Benzo(a)pyrene	2.08e-12 kg
Benzo(b)fluoranthene	6.12e-12 kg
Benzo(ghi)perylene	3.77e-13 kg
Benzo(k)fluoranthene	4.43e-12 kg
Beryllium	2.97e-09 kg
Cadmium	6.87e-09 kg
Carbon dioxide, fossil	0.838 kg
Carbon dioxide, non-fossil	0.0155 kg
Carbon monoxide, fossil	0.000489 kg
Chromium	2.1e-09 kg
Chromium VI	5.44e-10 kg
Chrysene	5.65e-13 kg
Cobalt	3.98e-09 kg
Copper	1.42e-08 kg
Dibenz(a,h)anthracene	2.88e-12 kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	9.43e-13 kg
Fluoranthene	4.72e-11 kg
Fluorene	4.28e-11 kg
Hydrogen chloride	6.63e-06 kg
Indeno(1,2,3-cd)pyrene	1.13e-12 kg
Lead	8.39e-08 kg
Manganese	5.74e-10 kg
Mercury	3.25e-08 kg
Methane, dichloro-, HCC-30	5.18e-08 kg
Methane, fossil	8.79e-06 kg
NMVOC, non-methane volatile organic compounds.	5.59e-05 kg
Nickel	6.71e-09 kg
Nitrogen oxides	0.00109 kg

Emissions to air	**Amount**
PAH, polycyclic aromatic hydrocarbons	1.27e-12 kg
Particulates, > 10 um	2.37e-05 kg
Particulates, < 2.5 um	6.5e-06 kg
Particulates, > 2.5 um, and < 10um	7.86e-06 kg
Phenanthrene	6.6e-10 kg
Phosphorus	3.48e-13 kg
Pyrene	3.44e-11 kg
Selenium	1.98e-09 kg
Sulfur dioxide	0.000392 kg
Thallium	1.3e-08 kg
Tin	9.05e-09 kg
Vanadium	4.97e-09 kg
Water	0.000294 m3
Zinc	6.34e-08 kg
Emissions to water	**Amount**
Arsenic, ion	1.29e-10 kg
Cadmium, ion	2.59e-11 kg
Chromium, ion	5.18e-11 kg
Copper, ion	2.59e-11 kg
Lead	2.72e-11 kg
Mercury	2.72e-13 kg
Nickel, ion	2.59e-11 kg
Phosphorus	7.77e-11 kg
Water	0.00165 m3
Zinc, ion	5.18e-11 kg
Output to Technosphere: waste and emissions to treatment	**Amount**
Inert waste, for final disposal	0.0001787 kg
Municipal solid waste	1.9013E-7 kg

Table 1.
Production data of 1 kg of clinker.

modeled for the world without Europe, US, Switzerland, China, India and it is valid from 2005 to 2018.

This dataset was created as a weighted average of the regional clinker production activities. The activities end with the cooling of the produced clinker. It includes the whole manufacturing process to produce clinker (raw material provision, grinding and mixing; rotary kiln process), internal processes (transport, etc.) and for the infrastructure only the rotary kiln (material consumption) is taken into account [46]. No administration is included. Waste (as secondary fuel and raw material) enter the system without environmental burdens from upstream processes. After the production of clinker, cement was thereafter produced. **Table 2** represents the production data of 1 kg of cement [47].

Inputs from Technosphere	Amount
Cement factory	5.36e-11 unit
Clinker	0.902 kg
Electricity, medium voltage	0.0376 kWh
Ethylene glycol	0.00019 kg
Gypsum, mineral	0.0475 kg
Limestone, crushed, for mill	0.05 kg
Steel, low-alloyed	0.00011 kg
Emissions to air	**Amount**
Heat, waste	0.135 MJ

Table 2.
Production data of 1 kg of Portland cement.

3. Results

3.1 Midpoint (process-oriented) approach

The midpoint approach presents the results of the impact categories in 2 tiers i.e., characterization and normalization. Normalization is based on the normalization factor which is the annual percentage of damage per capital which is the combination of different impact categories. The normalization factor is highly subjective and often set by method or software producers. Therefore, only characterization will be analyzed in details in this study to reduce uncertainties and also for proper understanding.

Table 3 gives a better insight as the values are given based on the amount of impact for every 1 kg of OPC produced. Environmental impacts are categorized into 18 categories based on their contribution as seen. As said above, different impact categories have their own equivalence (units). The Global warming, terrestrial ecotoxicity and resource scarcity are the impact categories with the highest impacts. These Impact hotspots will further be analyzed to know the production process and substance causing these emissions and bringing about these environmental consequences.

Global warming brings about climate change which affects both human health and species. **Table 3** shows that for every 1 kg of OPC produced, 0.911 kg of CO_2 equivalent is emitted during the production process. This implies that there is a very high tendency of global warming when cement as low as 1 kg is produced as a result of enormous CO_2 that is emitted. This result is further analyzed to know the production process and substances causing this emission. Specification to process gives us information about the particular production process that contributes to the impact category and specification to substance gives the particular substance that is emitted or that affects the impact category. **Tables 4** and **5** show the specification to substance and specification to process respectively. While the former gives insight to the particular amount of CO_2 emitted and the CO_2 equivalent, the latter shows the particular production process that produces these emissions.

Table 4 shows that 97.1% of CO_2 is produced while less than 3% are other gases. **Table 5** shows that 85.6% of 97.1% CO_2 seen as in **Table 2** was produced during clinker production phase of 1 kg of OPC that was produced. The specification to process of global warming in **Table 6** shows that 83.2% of clinker production brings about global warming.

S/N	Impact category	Unit	Portland cement
1	Global warming	kg CO_2 eq	0.911
2	Stratospheric ozone depletion	kg CFC 11 eq	7.84E-8
3	Ionization radiation	kBq Co-60 eq	0.00127
4	Ozone formation, Human health	kg NOx eq	0.00145
5	Fine particulate matter formation	kg PM2.5 eq	0.000577
6	Ozone formation, Terrestrial ecosystem	kg NOx eq	0.00147
7	Terrestrial acidification	kg SO_2 eq	0.0014
8	Freshwater eutrophication	kg P eq	1.16E-5
9	Marine eutrophication	kg N eq	3.56E-7
10	Terrestrial ecotoxicity	kg 1,4-DCB	0.438
11	Freshwater ecotoxicity	kg 1,4-DCB	9.92E-5
12	Marine ecotoxicity	kg 1,4-DCB	0.000383
13	Human carcinogenic toxicity	kg 1,4-DCB	0.00121
14	Human non-carcinogenic toxicity	kg 1,4-DCB	0.0153
15	Land use	m2a crop eq	0.00365
16	Mineral resources scarcity	kg CU eq	0.00464
17	Fossil resources scarcity	kg oil eq	0.0784
18	Water consumption	m^3	0.00185

Table 3.
Impact assessment table of 1 kg Portland cement using midpoint LCIA method.

S/N	Substance	Portland cement (%)
	Total of all compartment	100
	Remaining substances	0.102
1	Carbon dioxide, fossil	97.1
2	Methane, fossil	2.61
3	Dinitrogen monoxide	0.156

Table 4.
Specification to substance of global warming.

S/N	Process	Portland cement (%)
	Total of all processes	100
	Remaining processes	2.8
1	Clinker production	85.6
2	Diesel, Burned in building machine	2.8
3	Electricity high voltage	6.7
4	Heat	2.11

Table 5.
Specification to process of carbon dioxide (fossil) in global warming.

S/N	Substance	Portland cement (%)
	Total of all processes	100
	Remaining processes	15.23
1	Clinker production	83.2
2	Diesel, Burned in building machine	0.519
3	Electricity high voltage	0.418
4	Heat	1.41

Table 6.
Specification to process of global warming.

S/N	Substance	Cement portland (%)
	Total of all compartments	100
	Remaining substances	0.083
1	Beryllium	0.22
2	Cadmium	1.06
3	Chromium	0.208
4	Cobalt	0.149
5	Copper	61.5
6	Lead	2.56
7	Mercury	11
8	Nickel	7.53
9	Selenium	0.34
10	Thallium	0.158
11	Tin	0.301
12	Vanadium	7.06
13	Zinc	7.77

Table 7.
Specification to substance of terrestrial ecotoxicity.

Terrestrial ecotoxicity affects terrestrial species and it is measured by the quantity of 1,4-dichlorobenzene (DCB) produced. **Table 1** shows that for every 1 kg of OPC produced, 0.4381 kg of 1,4 DCB equivalent is produced to the terrestrial body. The specification to substance of terrestrial ecotoxicity that contributed to the overall amount of DCB with 61.5% of copper is shown in **Table 7**. The rest of the percentage comes from heat/power generation, ammonia emission, break wear emissions, electricity and some other with minimal emissions. **Table 8** shows the contribution of different stages of production with copper having the highest percentage of 38.72% while Clinker and brake wear emissions, lorry are 16.6% and 16.47% respectively. The rest of the percentage comes from heat/power generation, ammonia emission, electricity and some other with minimal emissions.

Fossil resource scarcity results to unavailability of fuel resources such as oil, gas and coal energy. It thereby increases the cost of available ones. It is measured by the quantity of oil produced per 1 kg of OPC produced. **Table 9** shows that crude oil (43.7%), coal (43.2%) and natural gas (13.1%) are substances that are used up

S/N	Process	Cement portland (%)
	Total of all compartments	100
	Remaining processes	9.74
1	Ammonia, liquid	0.949
2	Brake wear emissions, lorry	16.47
3	Clinker	16.6
4	Copper	38.72
5	Diesel burned in building machine	0.742
6	Electricity (high voltage)	2.093
7	Ferronickel, 25% Ni	2.92
8	Heat	2.482
9	Heavy fuel oil	1.44
10	Zinc	1.13

Table 8.
Specification to process of terrestrial ecotoxicity.

S/N	Substance	Portland cement (%)
	Total of all compartments	100
1	Coal	43.21
2	Gas, natural/m3	13.1
3	Oil, crude	43.7
4	Peat	0.00681

Table 9.
Specification to substance of fossil resource scarcity.

S/N	Process	Cement portland (%)
	Total of all processes	100
	Remaining processes	11.6
1	Hard coal	37.01
2	Lignite	1.6
3	Natural gas	8.22
4	Petroleum	41.57

Table 10.
Specification by process of fossil resource scarcity.

which eventually result into scarcity. **Table 10** shows almost the same result with 41.57% Petroleum, Coal 37% and Natural gas 8.22%.

3.2 Endpoint (damage oriented) approach

This approach presents several impact categories which is further classified into their various damage categories. The analysis in this approach is majorly on the

AoSL (damage category). It also shows impacts at different categories but eliminates other aspects without the knowledge of emission factors [37]. **Table 11** give the characterization result of the analysis of 1 kg of OPC. This presents 22 environmental impact categories with three specific damage units based on their effects.

The characterization result of the impact assessment represented in **Table 11** gives insight into each of the impacts in the damage category with the individual units of the impact showing what is affected. With their units in view, these impact categories were thereafter classified into their damage categories. This is represented in **Table 12**.

The damage assessment as shown in **Table 12** gives a summary of the damage category each of the impact categories in the characterization falls under, which are

S/N	Impact category	Unit	Portland cement
1.	Global warming, Human health	DALY	8.45E-7
2.	Stratospheric ozone depletion	DALY	4.16E-11
3.	Ionizing radiation	DALY	1.08E-11
4.	Ozone formation Human health	DALY	1.32E-9
5.	Water consumption Human health	DALY	2.69E-9
6.	Fine particulate Formation	DALY	3.62E-7
7.	Human carcinogenic toxicity	DALY	4.02E-9
8.	Human non-carcinogenic toxicity	DALY	3.49E-9
9.	Global warming, Terrestrial ecosystems	Species/yr	2.55E-9
10.	Global warming, Freshwater ecosystems	Species/yr	6.97E-14
11.	Ozone formation Terrestrial ecosystems	Species/yr	1.89E-10
12.	Terrestrial acidification	Species/yr	2.96E-10
13.	Freshwater Eutrophication	Species/yr	7.74E-12
14.	Marine Eutrophication	Species/yr	6.05E-16
15.	Terrestrial ecotoxicity	Species/yr	4.99E-12
16.	Freshwater ecotoxicity	Species/yr	6.88E-14
17.	Marine ecotoxicity	Species/yr	4.02E-14
18.	Land use	Species/yr	3.24E-11
19.	Water consumption, Terrestrial ecosystems	Species/yr	1.72E-11
20.	Water consumption, Aquatic ecosystems	Species/yr	1.17E-11
21.	Mineral Resource scarcity	USD2013	0.00107
22.	Fuel resource scarcity	USD2013	0.022

Table 11.
Impact assessment of 1 kg Portland cement using endpoint LCIA method.

S/N	Damage category	Unit	Portland cement (%)
1	Human health	DALY	$1.22E^{-6}$
2	Ecosystem	Species/yr	$3.1E^{-9}$
3	Resources	USD2013	0.0231

Table 12.
Damage assessment of 1 kg Portland cement using endpoint LCIA method.

Human health, Ecosystem and Resources. Human health has a value of $1.22E^{-6}$ DALY, Ecosystem of $3.1E^{-9}$ species/yr., Resources of 0.0231 USD 2013.

Thus, further detailed analysis was carried out on the damage assessment. The specification to process of human health as shown in **Table 13** reveals that 70.1% of the damage caused on human health is from the clinker production process. Others are from energy generation: diesel (4.02%), electricity (11.1%), hard coal (4.9%), heat (4.5%) and transportation (1%). This is as a result of the emission of primary gases such as CO_2, SO_2, NO_2, particulate matter and water. The specification to substance presented in **Table 14** shows that 67.3% of the damage is as a result of CO_2 emission with other substances such as Nitrogen oxides (8.23%), Sulfur dioxide (12.2%), particulate matter <2.5 μm (9.01%), water (2.5%).

Also, the specification to process of the damage to the ecosystem summarized in **Table 15** opined that 77.8% of the total damage to the ecosystem originates from the clinker production process as observed in the case of human health, a large portion of the remaining percentage is from energy generation (Diesel is 1.81%, electricity 7.7%, hard coal 2.8%, heat 2.6%) during which primary gases (CO_2, SO_2, NO_2) are emitted; 2.2% is from transportation. The Specification to substance analysis of damage to the ecosystem is presented in **Table 16**. CO_2 constitutes the highest emission percentage which is 79.9%, and other substances constitute the rest of the percentages. These other substances are Nitrogen oxides, constituting 9.48%, Sulfur dioxide is 5.6%, methane 2.1%, water 1.2%. These emissions are often emitted into the water body and the environment (air).

Table 17 presents specification to process of damage to resources. This shows that the major resource deletion is from Petroleum (65.8%), natural gas (11.3%),

S/N	Process	Portland cement (%)
	Total of all processes	100
	Remaining processes	4.38
1	Clinker	70.1
2	Diesel burned in building machine	4.02
3	Electricity, high voltage	11.1
4	Hard coal mine operation	4.9
5	Heat, district, or industrial	4.5
6	Transport freight	1

Table 13.
Specification to process of human health.

S/N	Substance	Portland cement (%)
	Total of all compartment	100
	Remaining substances	0.79
1	Carbon dioxide, fossil	67.3
2	Nitrogen Oxides	8.23
3	Particulates, <2.5 μm	9.01
4	Sulfur dioxide	12.2
5	Water	2.5

Table 14.
Specification to substance of human health.

S/N	Process	Portland cement (%)
	Total of all processes	100
	Remaining processes	5.09
1	Clinker	77.8
2	Diesel burned in building machine	1.81
3	Electricity, high voltage	7.7
4	Hard coal mine operation	2.8
5	Heat (Natural gas)	2.6
6	Transport, freight	2.2

Table 15.
Specification to process of ecosystems.

S/N	Substance	Portland cement (%)
	Total of all compartment	100
	Remaining substances	1.72
1	Carbon dioxide, fossil	79.9
2	Nitrogen Oxides	9.48
3	Sulfur dioxide	5.6
4	Methane	2.1
5	Water	1.2

Table 16.
Specification to substance of ecosystems.

S/N	Process	Portland cement (%)
	Total of all processes	100
	Remaining processes	0.6
1	Clay	4.1
2	Hard coal	11.8
3	Natural gas,	16.7
4	Petroleum production, on-shore	66.8

Table 17.
Specification to process of resources.

S/N	Substance	Portland cement (%)
	Total of all compartment	100
	Remaining substances	0.473
1	Clay	4.19
2	Coal, hard	11.4
3	Gas, natural/m^3	16
4	Oil, crude	67.9

Table 18.
Specification to substance of resources.

hard coal (8.8%), clay (4.2%) and the specification to substance; **Table 18** revealed the same substances as well.

4. Discussion

4.1 Midpoint

The characterization result of the midpoint analysis as presented in **Table 3** shows that the impact category: global warming is as a result of 0.911 kg of CO2 eq emitted into the air. The consequential effect of global warming is the change in the climatic conditions. Several studies that have been carried out estimated the impact of climatic changes from the production of cement within the range of 0.628 kg CO2 eq −0.920 kg CO2 eq (though their evaluation was with respect to 1ton of cement proceed) per kg of cement produced [10, 24, 35, 48–52]. Ozone formation, Human health and Ozone formation, Terrestrial ecosystem are as a result of 0.00145 kg NOx eq and 0.00147 respectively per kg of OPC. This impact category is measured with NOx emission into the air and also showed it affects human beings. This is one of the main air pollutants which when react with atmospheric air to produce nitrogen dioxide in which its high concentration in human body when inhaled has both direct and indirect effect on humans. It causes death in species and causes health complication on human. 0.000577 kg PM2.5 eq causes Fine particulate matter formation impact for 1 kg of OPC produced. This means that particulate matter with sizes less than 2.5 micrometer is emitted into air. Due to the small sizes of this particle, they have the ability to go through the nasal cavity of human and affect the lungs and other health issues. This value of fine particulate matter in this study is in line with values in literature within the range of 0.00023–0.0015 kg PM2.5 eq per kg of OPC [36, 52]. The result of terrestrial acidification in this study is 0.0014 SO2 eq and is in line with result of Li et al. (2015) which was in the range 1.144–1.467 kg SO2 eq per kg of OPC [35]. SOx emission is often from the burning of fuel with high Sulfur content and it has high tendency to cause acid rain and other health issues. Emission of 0.00127 kBq Co-60 eq give rise to Ionization radiation. 1 kg of OPC produced emits 0.00127 kilo-Becquerel of Cobalt 60 eq.; this can cause acute radiation, sick burn and even death. **Table 3** also showed that per kg of OPC produced, about 0.455 kg 1,4 DCB eq of different toxicity is emitted in to air and water. 1,4 DCB eq represents 1,4 dichlorobenzene equivalents. This is higher than values found in literature. This might be due to energy sources and fossil fuel mix [48, 53]. High toxicity in the environment (air and waterbodies) have effect on both human and ecosystem. Its health implication is wide-ranging and often times terminal. Pandemic in the aquatic community is often time traced to toxicity. Water consumption during the production of cement is 0.00185 m3: it was found to be comparable with that of Tun et al. and Chen et al. which was within 0.00019-0.00187 m3 [52, 53]. Also 0.0784 kg oil eq of Fossil resources scarcity is expected for every 1 kg of OPC produced. This resonates with the value from the study of [48, 53] with values ranging from 0.07 to 0.234 kg oil eq.; the three impacts categories with high environmental impacts are human health, terrestrial ecotoxicity and Fossil resources scarcity. In order to understand and recognize key factors responsible for these major impact categories, a further contribution analysis was carried out to show that exact substances and process stage contributing to these impacts and their level of contribution.

Global warming impact category results from the emission of 0.911 kg of CO_2 eq as seen in **Table 3**. The exact substances that give rise to 0.911 kg of CO_2 eq is as represented in **Table 4**. As presented in this table, 97.1% of 0.911 is from actual emission of CO2 i.e., 0.885 kg of CO_2 is emitted per kg of OPC produced. The remaining 0.026 kg of CO_2 eq is from the emission of CH_4 and N_2O. These gases (CO_2, CH_4 and N_2O) are major GHGs, though N_2O and CH_4 have high capacities to cause global warming: about 25 and 300 respectively, the larger emission of CO_2 cause explains why it's the major greenhouse gas that give rise to global warming and consequently climatic changes. The production processes in which these emissions are produced are as presented in **Table 5**. 83.2% of 0.911 kg CO_2 eq is from the clinker production phase (both from calcination and burning of fuel) i.e., 0.758 kg of CO_2 eq is produced at the clinker production phase and the remaining 0.153 kg of CO_2 eq is from various energy sources. A further analysis on co2 emission represented in **Table 6** reveals that 85.6% of the total CO2 emitted during the production of 1 kg of cement (0.885 kg) is emitted at the clinker production phase i.e., 0.75.8 kg of CO_2 is emitted at the clinker production stage. Recall that 0.758 kg of CO_2 eq is produced at the clinker production phase. This further analysis therefore shows that 0.76 kg of actual CO_2 emitted per kg of OPC produced is from clinker production stage. These results are comparable with that of most studies though the result of this study is lower that Stanford's result [48]. In this case more emissions of CO_2 are experienced in burning of fuels for the road transportation of clinker. Clinker used for the production of cement in this Brazilian cement plant are imported and on-road transportation being one of the major pollutants and CO_2 emitters, higher carbon footprint from this cement plant is inevitable.

Terrestrial ecotoxicity impact category as presented in **Table 3** is as a result of emission of 0.4381 kg of DCB equivalent which is produced into air. **Tables 7** and **8** represent further analysis to know the exact substance and production process respectively contributing to this impact. **Table 7** helps us to know that these impacts are as a result of emissions of heavy metals into the air. Copper has the highest value of 61.5% of all these metals and they all have different effects on both human and the ecosystem having established that whatever affects human affects the ecosystem and vice versa. **Table 8** on the other hand showed the production processes in which the emissions are produced. This shows that the raw material extraction stage (copper production), clinker production and the transportation (break wear emission, lorry) have the highest percentage contributions while others are majorly from energy sources and raw material extraction.

Fossil resource scarcity shows results represent the potential lack of scarcity that can be experienced per kilogram of cement produced. From **Table 3**, 0.0784 kg oil eq becomes scarce per kg OPC produced. This because 43.21% of coal, 43.1% of oil, 13.1% of natural gas are burnt during the production of 1 kg of OPC. This is represented in **Table 9**. These substances are used up at the energy generation phase (in this case are hard coal, petroleum, lignite and natural gas) of the cement production process as represented in **Table 10**.

4.2 Endpoint

Endpoint analysis categorizes the numerous impact categories into their damage categories based on the effects caused. This is represented in **Table 11**. Further analysis was carried out to show the exact substances production process stage contributing to these damage categories and their level of contribution. Damage to Human health as represented in **Table 11** has a value of $1.22E^{-6}$ DALY per kg of OPC produced. As seen in the midpoint analysis, clinker production stage has high contribution; in **Table 13**, clinker production contributes immensely to the damage of human health: 70.1% of damage to human health is from the clinker production process, 24.52% is from energy generation (electricity and fossil fuel) and 1% is from transportation. The substances that are emitted in this production process stages that cause this damage is represented in **Table 14**. Again, just as in the midpoint analysis, CO_2 emission has high contribution; 67.3% of CO_2 emission causes damage to human health, other substances are Nitrogen oxides (8.23%), Sulfur dioxide (12.2%), particulate matter <2.5 μm (9.01%), water (2.5%); each of which have respective implications on human health.

Damage to Ecosystem as recorded in **Table 11** has a value of 3.1E^{-9} species/yr. per kg of OPC produced. **Tables 15** and **16** show the result of analysis of substance and process responsible for damage to ecosystem respectively. 77.8% of damage to Ecosystem is from the clinker production stage and other production stages are energy generation and transportation. 79.9 of CO2 gas is emitted and thereby cause damage to the ecosystem and other substances such as Nitrogen oxides: 9.48%, Sulfur dioxide 5.6%, methane 2.1% and water 1.2%. Again, this established the fact that whatever will affect ecosystem will affect human health and vice-versa. **Table 11** showed that the potential marginal price increase of Resources per kg of OPC produced is 0.0231 USD (2013). This means that every resource used to produce 1 kg of OPC, poses an increase in the price of those resources by 0.0231 USD (2013). Further analysis to know what these resources are presented in **Table 18** shows that they are crude oil (67.9%), natural gas (16%), hard coal (11.4%) and clay (4.19%). The result of the specification to process represented in **Table 17** shows that about the same percentage amount of the substance is used in the energy generation stage and resource extraction (clay).

The result of the endpoint analysis is comparable with results of literature with CO2 emission and the clinker production stage being the highest contributors [52, 53]. There is variation in the resources of Chen et al. and Tun et al., this is because coal was the major source of fossil fuel for the production of cement.

5. Conclusion

This study carried out a LCA assessment on 1 kg of OPC so as to analyze the environmental impact of cement production using both the midpoint (process-oriented) and endpoint (damage-oriented) approaches. The production process modeled after the rest of the world excluding China, India, Europe, US and Switzerland; therefore, dataset modeled after the world was used to carry out the assessment. This dataset was extracted from Ecoinvent database incorporated in the SimaPro 9.0.49 software was used for this study.

In the midpoint assessment, characterization result showed the impact of 18 impact categories. The top three with highest impacts: global warming (0.911 kg CO2 eq), terrestrial ecotoxicity (0.438 kg 1,4-DCB), and fossil resources scarcity (0.0784 kg oil eq) were further analyzed. Global Warming has the highest environmental impact of 0.911 kg CO2 eq. Global warming is often times a result of high GHG emission and its effect is seen in changes in climatic conditions. Further analysis on this impact category shows 88.5 kg out of 0.911 kg CO2 eq is the actual CO2 gas emitted and 75.6 kg out of 88.5 kg of CO2 was emitted from the clinker production phase. This shows that clinker production is the production phase that contributes the most to global warming. In the analysis of terrestrial ecotoxicity, result showed that numerous heavy metals that that are emitter into the air are great contributors to this impact category; few of these metals with high values are copper (61.5%), Mercury (11%), zinc (7.77%), nickel (7.53%), vanadium (7.06%). These metals are emitted at the raw material extraction, energy generation and transportation production phases. Fossil resource scarcity shows that the most used resources are coal, crude oil and natural gas and they are maximally used at the energy generation production stage.

In the endpoint assessment, characterization result showed the impact of 22 impact categories. These impacts were further classified into three damage categories based on area of significance to life (AoSL): human health, ecosystem and resources with values of 1.22E^{-6} DALY, 3.1E^{-9} species/yr. and 0.0231 USD2013 respectively. Disability-adjusted life years (DALY) represents the years of life spent or years of life damaged because of environmental impacts. Species/yr. denotes the species lost within a year in water bodies and the environment as a whole; USD2013 represent the currency used for the monetary value of economic loss leading to increase in prices as a result of continuous extraction of resources. Analysis of the damage to human health category showed that 67.3% of the damage to human health is as a result of emission of CO2 while the rest are from NOx, so2 ch4, particulates mater <2.5 μm and water; 70.1% of these emissions was from clinker production stage while the rest was for energy generation and transportation. The same trend was observed in the analysis of damage to ecosystem; 79.9% of the damage to ecosystem was found to be as a result of co2 emission while the rest are from NOx, SO2 CH4, methane and water; 77.8% of these emissions was from clinker production stage while the rest was for energy generation and transportation. This thereby establishes the fact that whatever will affect human health will equally affect ecosystem. As also seen in the midpoint emission, clinker production is the production phase has the highest contribution to impact consequently causing damage and CO_2 is the most significant pollutant. The analysis of resources shows that the resources that are maximally used are from the energy generation production phase and they are: crude oil (67.9%), natural gas (16%), hard coal (11.4%) and clay (4.19%). This shows that petroleum is the main fossil fuel used for the production of OPC.

The outcome reveals that emission from clinker production contributed immensely to global warming and consequently damage to human health and ecosystem. This study concludes that production processes with impact hotspots are clinker production and energy generation (fossil fuel and electricity) and the major pollutant is CO2 gas emission. The result of this study is in line with other similar studies (including those that do not implement the 2 approaches) carried out but there is variation in the result of the resources because of variation in the fossil fuel sources used for energy generation. Finally, it is recommended that using alternative fuels in place of fossil fuels can be a means to reduce the pressure on fossil resources. Incorporation of best available techniques (BAT) in cement production process, partial replacement of clinker constituent with pozzolans like fly ash are other strategies to reducing impact of cement production. Also, CO_2 gas emitted can be trapped, stored and used as input for industrial processes which will reduce global warming impact. Further study is the sensitivity analysis of environmental impacts of cement when alternative fuel and materials are used.

Acknowledgements

The authors gratefully acknowledge Durban university of technology for an enabling environment. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest

Authors declare that there is no conflict of interest with respect to the study.

DOI: http://dx.doi.org/10.5772/intechopen.98398

List of acronyms

LCA	Life cycle assessment
LCIA	Life cycle impact assessment
OPC	Ordinary Portland Cement
BAT	Best available techniques
ISO	International Standard Organization
LCI	Life Cycle Inventory
ReCiPe	an acronym for the developers: RIVM, Radboud University, CML and PRé Consultants
1,4 DCB	1,4-dichlorobenzene
AoSL	Area of significance to life.
DALY	Disability-adjusted life years

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