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The Environmental Profile of Clinker, Cement, and Concrete: A Life Cycle Perspective Study Based on Ecuadorian Data

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Abstract: Concrete is the most-used material in the construction industry, and the second most-used after water. Cement is the main component of concrete. A total of 8% of global CO_2 emissions correspond to the cement industry; CO_2 is the main greenhouse gas contributing to global warming. To mitigate climate change, it is necessary to design buildings with a lower environmental impact, and therefore, it is crucial to assess the environmental profile of the local production of construction materials. This study uses the life cycle assessment methodological framework to evaluate the environmental sustainability of the cement and concrete industry in Ecuador. The inventory accounts for 62.8% of national cement production, with data corresponding to 2019. The OpenLCA software was used to perform the life cycle inventory and impact assessment calculations. Eight impact categories were assessed, including Global Warming Potential (GWP). Clinker has a GWP result of 897.04 kg CO_2-Eq/ton. Hydraulic cement types MH, GU, and HE have GWPs ranging from 465.89 to 696.81 kg CO_2-Eq/ton. Results of ready-mixed concrete range from 126.02 to 442.14 kg CO_2-Eq/m^3. Reducing the content of clinker in cement and concrete should be the aim so as to improve their environmental profiles. This study contributes to the development of regional life cycle inventory data for Latin America. This research is the first to be developed regarding construction materials in Ecuador and contributes to the sustainable design of structures with pozzolan-lime cement and concrete.

Keywords: LCA; carbon footprint; cement; concrete; clinker

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1. Introduction

World population growth is expected to increase by 22% by 2050, from 7.6 to 9.7 billion people [1], leading to migration, urbanization, and the construction of cities [2]. As a result, the consumption of raw materials and greenhouse gas (GHG) emissions will increase. In 2015, the United Nations Member States approved 17 Sustainable Development Goals (SDGs) as part of the 2030 Agenda [3]. The understanding of the key trends in urbanization likely to unfold over the coming years is critical for the SDGs' implementation, with a particular focus on SDG 9: build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation; SDG 11: make cities and human settlements inclusive, safe, resilient, and sustainable; and SDG 13: take urgent action to combat climate change and its impacts [4].

Climate change has been a constant topic of debate, which is why the environmental impacts of industries are more perceived, and it has led to the introduction of legislation and incentives to regulate and reduce GHG emissions [5,6]. Reducing the emission of GHG from the construction sector is of the utmost importance. Thus, it is necessary to quantify GHG emission throughout its value chain [5].

Construction is one of the main economic sectors, contributing significantly to the increase of the gross domestic product of different countries [7]. The construction industry is a dynamic sector in economic growth due to increased investments in infrastructure, construction, energy, and transport. It is one of the most important sectors in Latin America, mainly due to its ability to generate jobs. In Ecuador, it represents 7.5% of the total suitable jobs for 2019 [8]. This activity is transversal to other strategic sectors, such as agriculture, industry, commerce, and services since they require buildings to develop their activities.

Cement is one of the most commercialized materials worldwide [9]. It is estimated that global cement consumption was 4.08 billion tons in 2019 [10]. Its use is essential in the manufacture of concrete, the construction phase, and the maintenance of buildings [5,11]. From 5 to 8% of global CO_2 emissions correspond to the cement industry [12–14] due to the calcination of limestone and the combustion of fossil fuels. Additionally, a large electricity supply is required for the limestone-, clinker-, and cement-crushing processes. Cement production consumes 7% of the global industrial energy [15]. Cement production also causes other environmental impacts in addition to GHG emissions [16]; for example, nitrogen oxides (NO_x) and volatile organic compounds (VOC) are generated that can produce photochemical ozone formation in the air. This, in contact with people, causes health problems [17] and affects ecosystems [18]. Nitrogen oxides (NO_x), ammonia (NH_3), and sulfur dioxide (SO_2) exposed in high concentrations to the soil cause acidification, which would cause problems in the growth and development of vegetation [19,20].

According to FICEM (2020), cement production in Ecuador for the year 2019 was 6030 thousand metric tons [21]. Cement production in the coastal zone of Ecuador has a production capacity of 5.4 million metric tons. The coastal zone, the north, and the center–south contribute 62.8%, 18.6%, and 18.6% of the volume of Ecuadorian cement, respectively [22]. Ecuador is the country in Latin America with the highest consumption per capita with 355 kg cement per capita, followed by Mexico and Peru with 343 and 333 kg cement per capita, respectively (adapted from FICEM, 2020). Orienting the construction industry in Ecuador towards sustainability is a significant challenge to include in national agendas, and determining the environmental performance of the raw material of this sector is the first step.

Concrete is a widely used material in construction, and it is composed mainly of cement, crushed stone, sand, and water. The combination, proportion, number of components, and additions of these raw materials will result in the final properties of the concrete [23,24]. The versatility in its manufacture, that can be on-site or ready-mixed, the ease of being molded into different shapes and sizes, combined with its mechanical properties, durability, chemical inertness, thermal energy storage, and cost make it an essential material in the construction sector [25–27]. It is the most-consumed material after water [28]; 30 billion tons of concrete are used every year, 3 times more than 40 years ago on a per capita basis [29]. This extensive use makes evaluating and analyzing its environmental impacts essential, considering concrete production and its impact on climate change [30]. In Ecuador, 86% of the structures built in 2019 were made of reinforced concrete, with a lesser proportion of metallic structures at 11%, and wood and others occupying 3% [31]. In recent infrastructure projects built in Ecuador, 29% of the total cost corresponds to concrete structures [32].

Life cycle assessment (LCA) is a tool that allows obtaining quantitative results when evaluating the environmental performance of a service or product in each of the stages of its life cycle [33]. Given the growing interest of government groups in the environmental impacts of the industry [34], LCA has been widely used for the generation of environmental product declarations (EPDs), particularly in the manufacture of materials [35]. In the last decade, the analysis of the environmental impacts of the cement industry has increased [16]. In Europe, LCAs for clinker production have been developed [36–38]; these results serve as input for the preparation of Portland cement (PC) or added cement. Some studies analyze ordinary Portland cement (OPC) as the main product, as well as the process and composition alternatives [36,38–41]. In Asia, OPC and proposals for environmental improvement measures are analyzed; others compare the environmental performance between cements [9,42–44]. In Latin America, there are fewer studies on the environmental performance of cement using LCA. In Peru, the GWP of the cement industry and the partial replacement of clinker with other additions, such as pozzolan, slag, and calcareous filler, has been studied using LCA methodology in bags of cement (42.5 kg) from 3 different plants, having results between 24–32 kg CO_2-Eq/cement bag (42.5 kg); adapting this result to tons, it is 564–752 kg CO_2-Eq/ton of cement [45]. Regarding ready-mixed concrete (RMX), studies from Europe and Asia have analyzed conventional concrete and concrete environmental improvements by adding waste, recycled components, using fly ash, slag, or combining these options [46–49], resulting in GWP reductions between 1 and 23% in similar, characteristic, compressive strength. For North America, South America, and South Africa, life cycle inventories [50–52] and LCA [53,54] for conventional concrete with characteristic compressive strengths produced results between 20 and 50 MPa.

Constructing structures for the development of human activities is a need; making it sustainable is a challenge for different stakeholders, such as the public and private sectors and academia. It is necessary to measure the environmental impact in the construction sector with tools such as LCA. There is no quantitative environmental performance information regarding the main construction material used in Ecuador. Therefore, it is essential to develop life cycle inventories of the main raw materials, those being clinker, cement, and ready-mixed concrete. This information will allow the calculation of the environmental performance of buildings and construction projects that will serve as a baseline for optimizing and reducing the environmental impact of construction. This study aims to quantify the environmental performance of clinker, cement, and ready-mixed concrete using the LCA methodological framework to identify hotspots in the studied systems.

2. Materials and Methods

2.1. Life Cycle Assessment

Life cycle assessment (LCA) is based on the guidelines of ISO 14040–14044, which describes four steps for its development: Goal and scope definition, Inventory analysis, Impact assessment, and Interpretation [55]. A life cycle includes stages such as the extraction of raw materials, production, product components and the product itself, use, and recycling or final disposal. It is important to note that it is not necessary to prepare an LCA with all the stages of the life cycle; it can be adjusted to the needs of the project. The life cycle inventory analysis is a compilation of all the environmentally relevant input and output of the system, which are obtained or adapted from primary and secondary data. All the input and output is quantified according to the functional unit. The impact assessment phase includes the use of characterization models, which include emissions and resource use factors that are used to transform the environmentally relevant input and output into the life cycle environmental impact indicator results. The use of LCA has been very useful in evaluating the performance of materials and energy in a system, the variations of the levels of environmental efficiency between processes, and generating baselines for future eco-efficient improvements [56].

Although LCA is the main tool to evaluate the environmental profile of product and services, including GHG emissions and carbon footprint, some authors have used some approaches that are not explicitly labeled as life cycle tools. Similarly, these tools quantify the GHG emissions with a focus on the product or service. Park et al. [57], in their study of metakaolin composite concrete, use emission factors adapted from Long et al. [58] for the calculation of CO_2 emissions, energy, and resource consumption [57,58]. Similarly, authors such as Ghalehnovi et al. [59] and Shamsabadi et al. [60] use a global warming index derived from Lippiatt [61], based on the GWP of each material and its weight.

Other authors have used an index, the Building Material Sustainability Potential (BMSP), which relates the structural performance, service life, and the environmental impact to describe the sustainability of a building material [62–64]. It should be noted that the GWP have been used as the descriptor of environmental performance, and that in LCA, the performance and service life of a building material should be expressed in the functional unit.

2.2. Scope

The study includes the extraction and processing of virgin raw materials; the processing of raw materials; the transportation of raw materials to the manufacturer; and the manufacturing of clinker, cement, and ready-mixed concrete. Three systems are studied: clinker, cement, and concrete (Figure 1). Primary data for all the systems is for the year 2019. The functional units are 1 ton of clinker, 1 ton of type GU (general use) cement, 1 ton of type HE (high early strength) cement, 1 ton of type MH (moderate heat of hydration) cement, under ASTM C1157 [65], and 1 m^3 of ready-mixed concrete (RMX) with characteristic compressive strengths between 2.5 and 80 MPa.

The systems studied for clinker and cement accounted for 62.8% of the cement used in Ecuador in 2019. The clinker, cement, and concrete systems have cradle-to-gate approaches. Technical system boundaries for clinker include extraction and transport of raw materials, fuels, rotary kiln, and cooling. Technical system boundaries for cement include the clinker system, additional raw materials, and cement manufacturing. The technical system boundaries for concrete include the cement system, aggregate production, transport to the concrete plant, concrete production, and recycling.

2.3. Life Cycle Inventory Analysis

2.3.1. Primary Data Collection

Material and energy inputs to produce clinker, cement, and concrete were obtained from plants' sustainability reports. Access was provided to the data of the registering system of raw materials consumption, fuels, and electricity use in each phase of the three systems. Monthly emission data for CO_2, NO_x, SO_2, PM, and VOCs was obtained from the continuous emission-monitoring system of each clinker kiln. Pollutant emissions such as ammonia, antimony, arsenic, benzene, cadmium, hydrogen chloride, cobalt, copper, chromium, dioxins, mercury, carbon monoxide, nickel, lead, thallium, and vanadium were obtained from the biannual measurement reports of each clinker kiln. Reports on the consumption of oils, heavy machinery, and maintenance equipment were obtained from logistics records. The average production of the last five years was used, and a life span of 50 years was used to include the construction of the production plants.

2.3.2. Secondary Data

The main components of the clinker production process are limestone, clay, and other mineral correctors. Life cycle inventory datasets for those were taken from ecoinvent 3.7.1 [66], considering the transport from each factory (see Table S1 in Supplementary Materials). In the cement production process, the raw materials, such as limestone and gypsum, were taken from ecoinvent 3.7.1 (see Table S2 in Supplementary Materials).

In the concrete manufacturing process, production of the tap water available for Peru (PE) and diesel for Colombia (CO) are used due to their geographical proximity, crushed stone, sand, and admixtures were used from global processes (see Table S3 in Supplementary Materials) available in ecoinvent 3.7.1 [66].

The electricity process was created by Ramirez et al. [67,68], who carry out a life cycle assessment covering all types of power plants available in the country, taking the national energy balance of 2018. Regarding diesel from Ecuador, the physical properties used for the calculation: density of 850 kg/m^3 and a heat capacity of 40.8 MJ/kg, available in reports from the Ministry of Energy and Non-Renewable Natural Resources [69].

2.4. Life Cycle Impact Assessment

The impact analysis method used is ReCiPe Midpoint (H) V1.13 [70]. The following impact categories are considered: global warming potential (GWP100), terrestrial acidification potential (TAP100), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), ozone depletion potential (ODPinf), photochemical oxidant formation potential (POFP), particulate matter formation potential (PMFP), and fossil depletion potential (FDP). It should be noted that the GWP category indicator results are often called "carbon footprint."

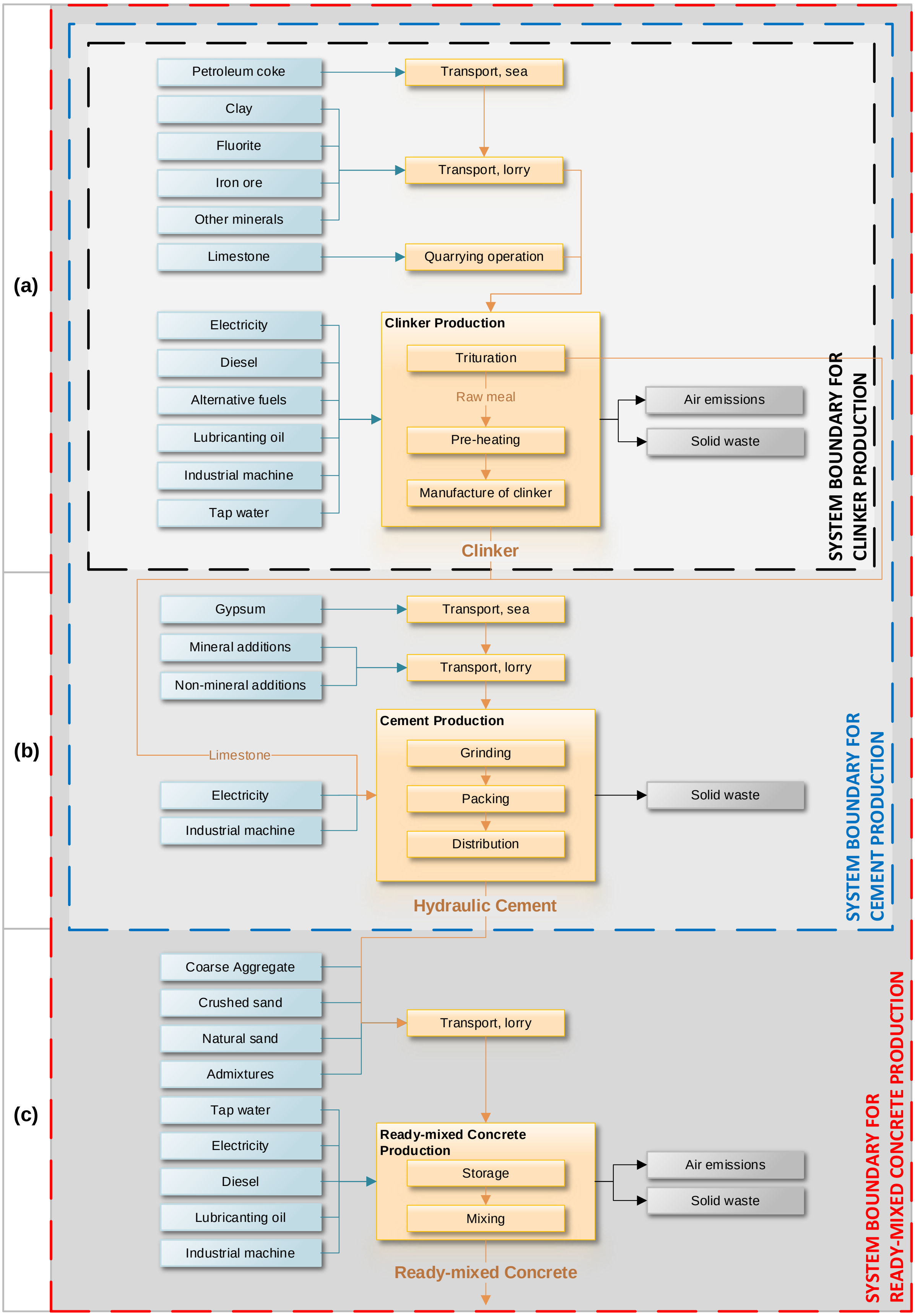

Figure 1. Cradle-to-gate system boundaries for the production of clinker, cement, and concrete in Ecuador: (**a**) clinker production, (**b**) cement production, and (**c**) ready-mixed concrete production.

Calculation

The software used for the life cycle inventory and impact assessment calculations is OpenLCA 1.10.3, GreenDelta, Berlin, Germany [71].

3. Results and Discussion

3.1. Life Cycle Inventory

In the production of clinker, 86% of the total raw materials are composed of limestone (the most used material). Four types of clays are used, which come from different parts of Ecuador; these clays represent 11% by mass, and other raw materials of mineral correction represent 3% (see Table S4 in Supplementary Materials).

The process that consumes the greatest amount of electricity is the manufacture of clinker, followed by the crude material mills. Using the heat capacity of fuels, petroleum coke and diesel represent 91.1% of thermal energy and 8.9% of alternative fuels. The clinker and cement manufacturing processes do not consume water as a raw material. The life cycle inventory for compound hydraulic cements from Ecuador is not presented because of a confidentiality agreement with the companies analyzed in this study.

In regard to ready-mix concrete, the city with the highest consumption is Guayaquil, with 38.1%, followed by Quito with 30.8%; other cities, such as Cuenca, Machala, Ambato, and Manta, represent 10.2%, 8.4%, 6.5%, and 6%, respectively. Conventional concretes (18–40 MPa) are the most-used in the construction industry in Ecuador, with 88% of the total studied, while high compressive strength concretes ($\geq$40 MPa), 6.5%, and low compressive strength concretes ($\leq$18 MPa), 5.5%. (Life cycle inventory is presented in Table S5 in Supplementary Materials).

The most-used concrete has a compressive strength of 28 MPa, representing 22.5% of national production. This concrete is typical in the construction of elements such as columns, beams, and building foundations. The second most-used concrete has a compressive strength of 21 MPa, with 20.1%, and is commonly used in slabs.

3.2. Life Cycle Impact Assessment

3.2.1. Clinker

The different stages of clinker production are classified and compared. Figure 2 shows the contribution result in the selected impact categories. Table 1 shows the environmental impact category indicator results for clinker.

Table 1. Result of life cycle assessment impact categories for 1 ton of clinker.

Impact Categories	Unit	This Study	Literature Reviewed
Global Warming Potential—GWP100	kg CO_2-Eq	897.04	850–929 [1]
Terrestrial Acidification Potential—TAP100	kg SO_2-Eq	1.52	8.41 [2]
Freshwater Eutrophication Potential—FEP	kg P-Eq	0.42×10^{-2}	1.21×10^{-2} [3]
Marine Eutrophication Potential—MEP	kg N-Eq	0.08	——
Ozone Depletion Potential—ODPinf	kg CFC^{-11}-Eq	4.51×10^{-5}	——
Photochemical Oxidant Formation Potential—POFP	kg NMVOC-Eq	2.08	1.24 [3]
Particulate Matter Formation Potential—PMFP	kg PM10-Eq	0.65	——
Fossil Depletion Potential—FDP	kg oil-Eq	86.48	——

[1] [36,37,40]; [2] [40]; [3] [41].

Regarding GWP100, the manufacture of clinker is the process with the highest contribution of GWP, with 842.69 kg CO_2-Eq/ton of clinker; this represents 93.9% of this indicator. This is due to the CO_2 generated in the clinker kiln by the combustion of petroleum coke and the release of CO_2 in the chemical process of the change of calcium carbonate ($CaCO_3$)

into calcium oxide (CaO) [72]. The production of petroleum coke is the second process with the highest contribution to GWP, resulting in 30.21 kg CO_2/ton of clinker and a share of 3.37%. Electricity supply contributes 1.19% to the GWP because 82% of the electricity mix in Ecuador in 2018 was hydropower [67]. In the literature, GWP results range between 850 and 929 kg CO_2-Eq/ton of clinker [36,37,40]; this study has a GWP result of 897.04 kg CO_2-Eq/ton of clinker, which is within the range found in the literature.

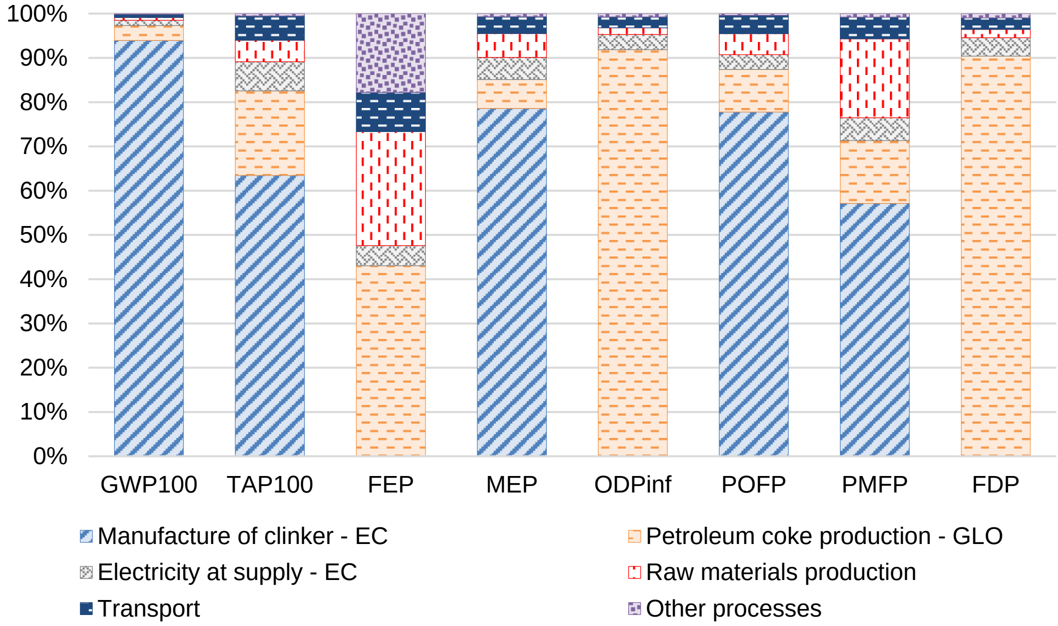

Figure 2. Contribution analysis for each environmental impact category for processes per ton of clinker (functional unit). GWP100: global warming potential; TAP100: terrestrial acidification potential; FEP: freshwater eutrophication potential; MEP: marine eutrophication potential; ODPinf: ozone depletion potential; POFP: photochemical oxidant formation potential; PMFP: particulate matter formation potential; FDP: fossil depletion potential; EC: Ecuador; and GLO: global.

Nitrogen oxides (NO_x), sulfur dioxide (SO_2), and ammonia (NH_3) are the main emissions contributing to TAP100, which are present in the flue gases from clinker kilns. This process contributes 0.964 kg SO_2-Eq/ton of clinker, corresponding to 63.5% of the indicator. The production of petroleum coke contributes 0.29 kg SO_2-Eq/ton of clinker, representing 19.25% of this category; the result is 1.52 kg SO_2-Eq/ton of clinker. Çankaya & Pekey [40] obtained results of terrestrial acid/nutri in 8.41 SO_2-Eq/ton of clinker for a traditional scenario, and 6.75 SO_2-Eq/ton of clinker for an alternative scenario, clinkerization contributes 75%, raw materials, 13%; and electricity, 6.5%. Most of the difference between Çankaya & Pekey [40] and this study is due to the composition of fossil fuels (such as petroleum coke, lignite, fuel oil, and natural gas) and the use of alternative fuels.

The results of FEP for this study are lower than García-Gusano et al. [41], with 0.42×10^{-2} kg and 1.21×10^{-2} P-Eq/ton of clinker, respectively. Figure 2 shows that the process with the greatest contribution is the manufacture of petroleum coke, with 43.04%, and electricity, 4.55% of the total FEP. García-Gusano et al. [41] found that the fossil fuel combustion and electricity consumed entail 40% and 37%, respectively. These differences are mostly due to the electricity mix and the efficiency of electrical consumption; this study has 71.24 kWh/t of clinker, and the Spanish industry has 92 kWh/t of clinker in 2010. Regarding MEP, the result obtained for Ecuador is 0.08 kg N-Eq/ton of clinker. The clinker production process contributes 78.6% to the MEP results due to the NO_x emitted during clinkerization.

The result for ODPinf is 4.51×10^{-5} kg CFC^{-11}-Eq/ton of clinker, and for FDP, it is 86.48 kg oil-Eq/ton of clinker. The dominant process in ODPinf is producing petroleum coke, and it is also dominant for the impact category FDP. Regarding POFP, the most contributing process is clinkerization, with 77.8%, due to the VOC in the gases emitted from the clinker kiln. García-Gusano et al. (2015a) obtained as a result 1.24 kg NMVOC-Eq/ton of clinker [41], a value close to the result of this study: 2.08 kg NMVOC-Eq/ton of clinker. The result for PMFP, 0.65 kg PM10-Eq/ton of clinker, is due to primary aerosols, such as PM, and secondary aerosols, such as SO_2, NH_3, and NO_x, present in the flue gases from clinkerization.

3.2.2. Cement

This study presents the environmental performance of the three most-sold types of cement in Ecuador. Type GU cement is the one with the highest consumption. The carbon footprint of cement in Ecuador ranges from 465.89 to 696.81 kg CO_2-Eq/ton (Table 2). The results for type GU were 545.78 kg CO_2-Eq/ton of cement. The GWP range for ordinary Portland cement ranges from 632 to 950 kg CO_2-Eq/ton of cement, according to the literature [36–40,45,73,74], while the GWP of cement with additions, such as pozzolan, slag, limestone, and fly ash, vary from 452 to 850 kg CO_2-Eq/ton of cement [36,40,45,53].

Table 2. Result of life cycle evaluation impact categories for 1 ton of composite hydraulic cement.

Impact Categories	Unit	This Study GU [1]	HE [2]	MH [3]	Literature Reviewed
Global Warming Potential—GWP100	kg CO_2-Eq	545.78	696.81	465.89	632–950 [4] 452–850 [5]
Terrestrial Acidification Potential—TAP100	kg SO_2-Eq	1.03	1.27	0.88	1.467–4.1 [6] 0.87–1.16 [7]
Freshwater Eutrophication Potential—FEP	kg P-Eq	3.59×10^{-3}	4.23×10^{-3}	3.22×10^{-3}	1.23×10^{-2} [8]
Marine Eutrophication Potential—MEP	kg N-Eq	0.054	0.067	0.047	–
Ozone Depletion Potential—ODP	kg CFC^{-11}-Eq	2.83×10^{-5}	3.59×10^{-5}	2.43×10^{-5}	9.60×10^{-9} 4.20×10^{-5} [9]
Photochemical Oxidant Formation Potential—POFP	kg NMVOC-Eq	1.34	1.68	1.16	1.09 [8]
Particulate Matter Formation Potential—PMFP	kg PM10-Eq	0.48	0.56	0.42	——
Fossil Depletion Potential—FDP	kg oil-Eq	54.85	69.30	47.14	——

[1] GU: General use cement; [2] HE: High early strength cement; [3] MH: Moderate heat of hydration cement; [4] Ordinary Portland cement, GWP results [36–40,45,73,74]; [5] Cement with additions, GWP results [36,40,45,53]; [6] [37,38,43,46,53,74]; [7] Cement with additions, TAP100 result [40]; [8] [41]; [9] [9,40,41,53,73].

The results of this study rank in the lower limits due to the levels of additions in the cement and because of the efficiency of the plant of 3.01 GJ/ton of cement in thermal energy consumption compared to that in the literature, that being from 2.81 to 5.4 GJ/ton of cement [43,74,75]. The clinker production process contributes 98% of the total GWP of the composite hydraulic cement in Ecuador (Figure 3) due to the GHG emitted in the clinkerization process, followed by the electricity generation process, with a range between 0.9 and 1.4%.

Regarding TAP100, the cement from Ecuador ranges between 0.88 to 1.27 kg SO_2-Eq/ton of cement. These values are close to those found in the literature, which are between 1.467 and 4.1 kg SO_2-Eq/ton of cement [37,38,43,46,53,74]. Çankaya & Pekey [40] report values between 0.87 to 1.16 kg SO2-Eq/ton for pozzolanic cements with similar additions and compositions to the ones in Ecuador. NO_x is the largest contributor to this category, followed by SO_2, both produced by the clinkerization process.

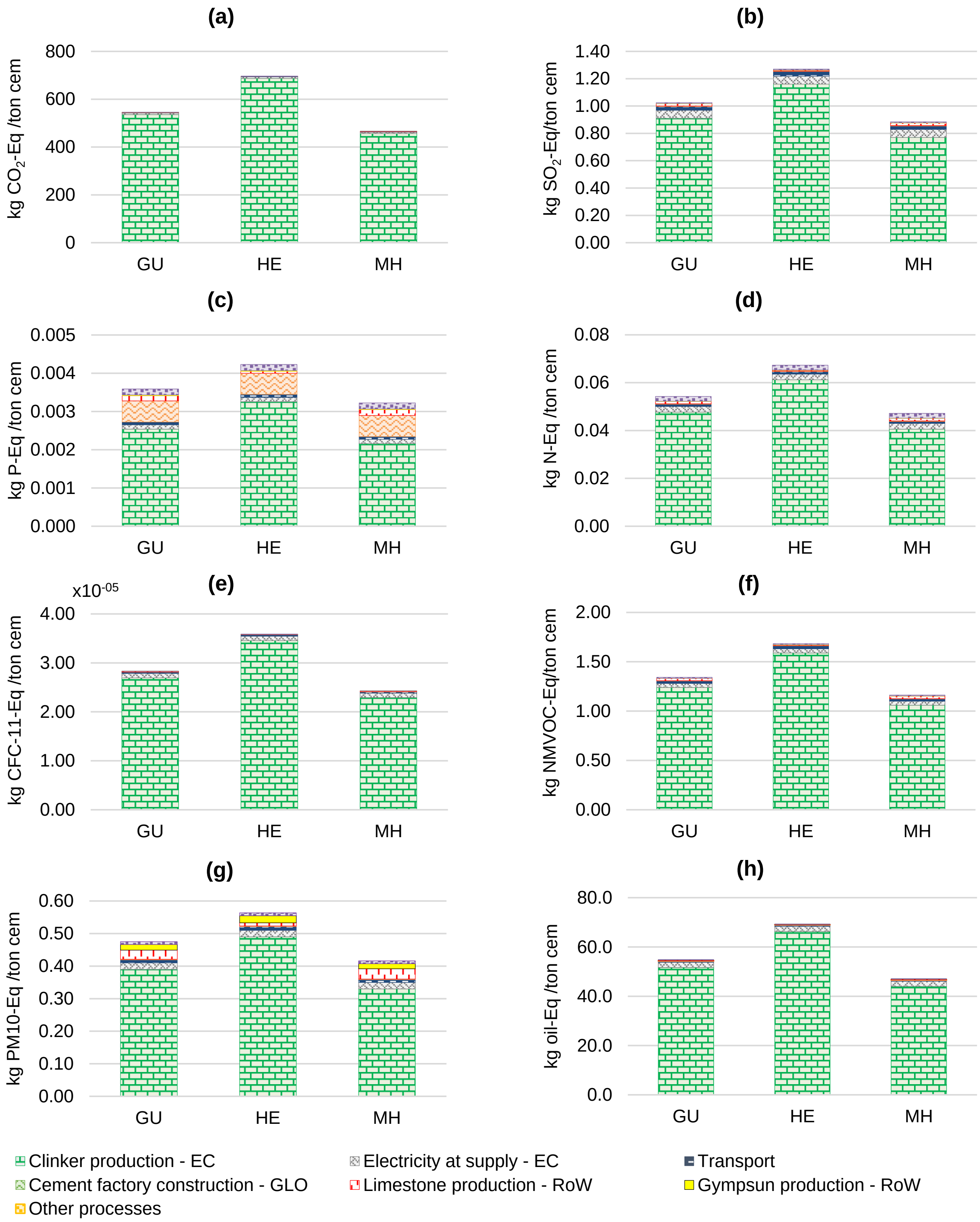

Figure 3. Characterization results for impact categories. The graphs show the impact results per ton of cement (functional unit) by type: GU: General use, HE: High early strength, and MH: Moderate Heat of Hydration, and a contribution analysis for processes. (**a**) Global warming potential—GWP100; (**b**) Terrestrial acidification potential—TAP100; (**c**) Freshwater eutrophication potential—FEP; (**d**) Marine eutrophication potential—MEP; (**e**) Ozone depletion potential—ODPinf; (**f**) Photochemical oxidant formation potential—POFP; (**g**) Particulate matter formation potential—PMFP; (**h**) Fossil depletion potential—FDP; EC—Ecuador; GLO—global; and RoW—Rest of world.

For the Spanish cement industry, García-Gusano et al. [41] calculated for freshwater eutrophication (FEP) a value of 1.23 × 10^{-2} kg P-Eq/ton of cement. This study determines values between 3.22 × 10^{-3} to 4.23 × 10^{-3} kg P-Eq/ton of cement. The process with the greatest contribution is the manufacture of clinker. Comparing both studies, the results are in similar ranges. In marine eutrophication (MEP), the results obtained are 0.047 to 0.067 kg N-Eq/ton of cement.

Results of ODPinf in Ecuadorian cements are between 2.43 × 10^{-5} and 3.59 × 10^{-5} kg CFC^{-11}-Eq/ton of cement. Literature results vary between 9.60 × 10^{-9} and 4.20 × 10^{-5} kg CFC^{-11}-Eq/ton of cement [9,40,41,53,73]. The process with the greatest contribution is clinker production. The same situation also occurs for FDP, as this category represents the depletion of fossil resources.

The results for POFP in this study ranged from 1.16 to 1.68 kg NMVOC-Eq/ton of cement due to the emissions of VOC, NO_x, and SO_2 from the manufacture of clinker. The result of POFP is similar to that obtained by García-Gusano et al. [41] of 1.09 kg NMVOC-Eq/ton of cement. Results of PMFP for cements in Ecuador are in the range of 0.42 to 0.56 kg PM10-Eq/ton of cement, with $NO_{X,}$ being the highest contributor to the flow followed by PM.

The critical input in the manufacture of cement in Ecuador is the clinker. Clinker has the greatest share in the impact categories analyzed, as shown in Figure 3.

3.2.3. Concrete

The impact category indicator results for 1 m^3 of ready-mixed concrete with characteristic compressive strengths between 2.5–80 MPa for Ecuadorian production are presented in Table 3. These results represent the average production of ready-mixed concrete in Ecuador, based on the distribution percentage of the concrete output per plant.

Table 3. Result of life cycle evaluation impact categories for 1 m^3 of ready-mixed concrete with different compressive strengths in Ecuador.

Compressive Strength	GWP100 kg CO_2-Eq	TAP100 kg SO_2-Eq	FEP kg P-Eq	MEP kg N-Eq	ODPinf kg CFC^{-11}-Eq	POFP kg NMVOC-Eq	PMFP kg PM10-Eq	FDP kg Oil-Eq
2.5 MPa	126.02	0.35	5.79 × 10^{-3}	0.019	0.93 × 10^{-5}	0.50	0.17	22.55
15 MPa	206.80	0.49	8.04 × 10^{-3}	0.027	1.35 × 10^{-5}	0.67	0.23	30.17
18 MPa	225.84	0.54	9.40 × 10^{-3}	0.029	1.45 × 10^{-5}	0.72	0.25	33.43
21 MPa	237.22	0.55	9.73 × 10^{-3}	0.030	1.50 × 10^{-5}	0.75	0.26	34.85
24 MPa	256.08	0.60	10.2 × 10^{-3}	0.033	1.63 × 10^{-5}	0.81	0.28	37.89
28 MPa	267.54	0.62	10.3 × 10^{-3}	0.034	1.66 × 10^{-5}	0.83	0.29	38.91
30 MPa	290.85	0.67	11.4 × 10^{-3}	0.036	1.85 × 10^{-5}	0.90	0.32	43.17
35 MPa	310.31	0.69	11.2 × 10^{-3}	0.038	1.88 × 10^{-5}	0.93	0.32	44.87
40 MPa	355.38	0.77	11.8 × 10^{-3}	0.041	2.07 × 10^{-5}	1.02	0.35	50.86
45 MPa	379.38	0.83	11.2 × 10^{-3}	0.045	2.29 × 10^{-5}	1.12	0.39	52.25
50 MPa	382.03	0.82	12.0 × 10^{-3}	0.044	2.23 × 10^{-5}	1.10	0.38	53.37
60 MPa	419.55	0.89	13.3 × 10^{-3}	0.048	2.40 × 10^{-5}	1.17	0.41	59.18
80 MPa	442.14	0.91	12.3 × 10^{-3}	0.048	2.46 × 10^{-5}	1.19	0.41	60.25

GWP100: global warming potential; TAP100: terrestrial acidification potential; FEP: freshwater eutrophication potential; MEP: marine eutrophication potential; ODPinf: ozone depletion potential; POFP: photochemical oxidant formation potential; PMFP: particulate matter formation potential; FDP: fossil depletion potential.

The results of GWP100 show that low compressive strength concrete (18 MPa>) has approximately 29% of the GWP of the high compressive strength concrete (>40 MPa); this is due to different cement contents (Figure 4). It can be seen that cement production is the critical process within this impact category, with an influence between 84 and 88% in conventional concrete (18 at 40 MPa). For low compressive strength concrete, cement production contribution is approximately 76% because there is greater use of fine aggregate instead of cement. For high compressive strength concrete, the consumption of cement increases; this causes that cement production to contribute 89–92%. Transport is the second process with the highest contribution in this category, with values between 1.13 and 8.30%. For high compressive strength concrete (>40 MPa), transport shows low contribution values (1.13–2.83%).

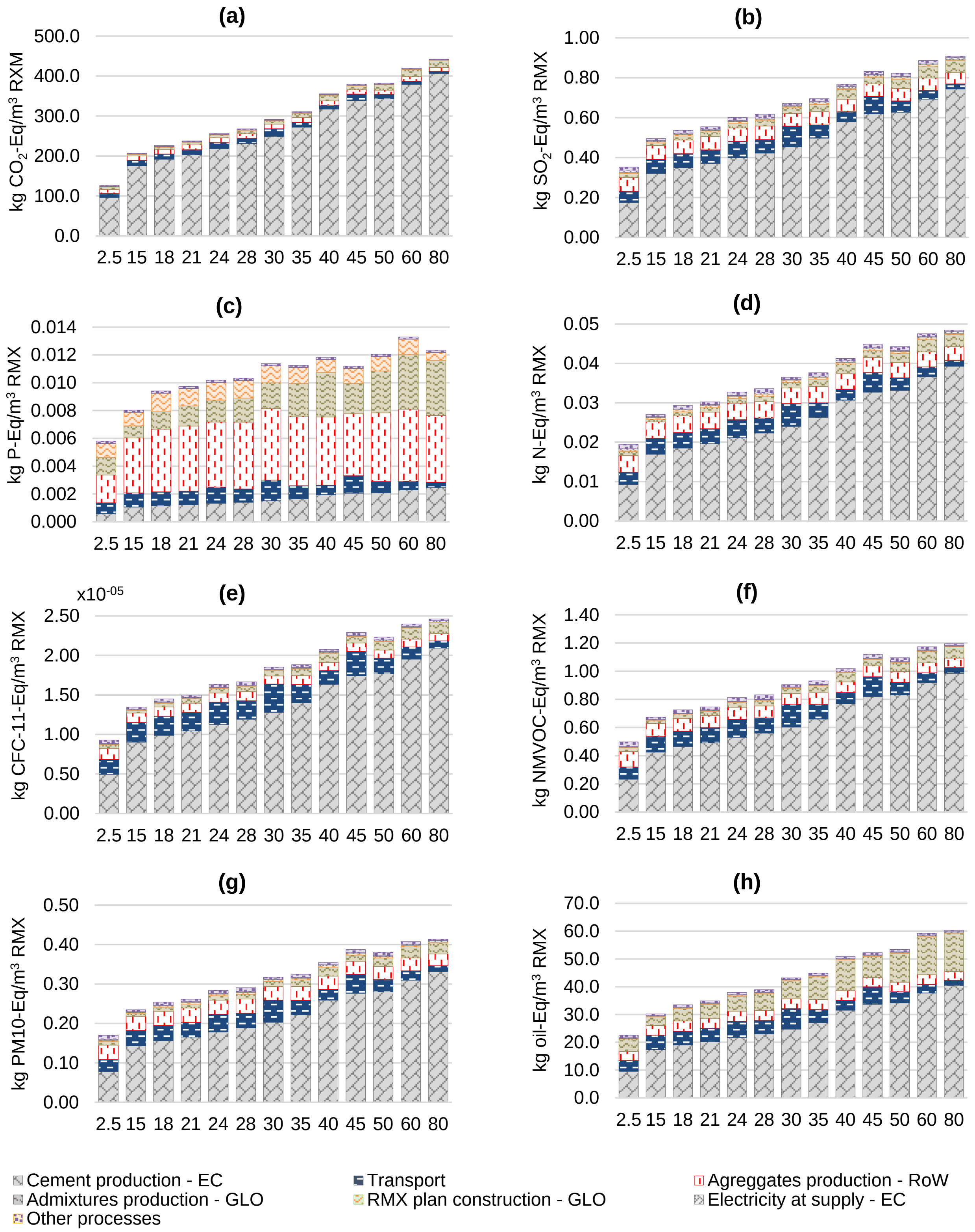

Figure 4. Characterization of results for impact categories. The graphs show the impact results per m^3 of ready-mixed concrete (functional unit) with compressive strength between 2.5 and 80 MPa and a contribution analysis for processes. (**a**) Global warming potential—GWP100; (**b**) Terrestrial acidification potential—TAP100; (**c**) Freshwater eutrophication potential—FEP; (**d**) Marine eutrophication potential—MEP; (**e**) Ozone depletion potential—ODPinf; (**f**) Photochemical oxidant formation potential—POFP; (**g**) Particulate matter formation potential—PMFP; (**h**) Fossil depletion potential—FDP; RMX: ready-mixed concrete; EC: Ecuador; GLO: global; and RoW: Rest of world.

The following two processes with significant contributions are aggregate production and admixture production. Within aggregate production, there is a consumption between 67 and 84% per m^3 of the concrete's total mass; also, there is a low amount of CO_2 emission per kg of aggregate. Admixture consumption is between 0.01 and 0.02% per m^3, with a high content of CO_2 emission per kg of admixture. Other processes, such as electricity, fuel, and water consumption represent between 0.5 and 2% of the GWP.

The results of terrestrial acidification–TAP100—vary between 0.35 and 0.91 kg SO_2-Eq/m^3 of ready-mixed concrete. Cement production is the critical process, with a contribution between 49.79 and 81.83%. The content (and contribution) is higher when higher characteristic compressive strength is required. TAP100 for transport increases for concrete plants where a greater distance from the cement factory is observed. The values of this study for characteristic compressive strengths between 21 and 50 MPa are 0.55–0.83 kg SO_2-Eq/m^3 of ready-mixed concrete, lower than studies from Colombia, Peru, South Africa, Brazil, and Canada for the same compressive strengths. The value of TAP100 varies from 0.622 at 1.73 kg SO_2-Eq/m^3 of ready-mixed concrete [50–52,54], due to low levels of SO_2 in flue gas from the production of clinker, due to the composition of fossil fuels and use of alternative fuels in kilns. This is reflected in the value chain of cementitious materials, such as concrete production, having lower TAP100 values than the literature reviewed.

For the freshwater eutrophication—FEP impact category, the values reported within this research range from 55.79×10^{-3} to 13.3×10^{-3} kg P-Eq/m^3 of ready-mixed concrete. The process with the highest contribution is aggregate production, with values between 34 and 49%. The production of crushed aggregate has a greater contribution than the production of natural sand. The second process with the highest contribution is admixture production, ranging between 10.96 and 32.10%. Results of marine eutrophication—MEP range from 0.019 to 0.048 kg N-Eq/m^3 of ready-mixed concrete. The critical process is the production of cement due to the NO_x emissions in the production of clinker. The value of other processes is relatively constant, with values between 0.009 and 0.011 kg N-Eq/m^3 of ready-mixed concrete. Gursel & Ostertag [76] in their study of ready-mixed concrete with OPC report values between 0.18 and 0.395 kg N-Eq/m^3 of ready-mixed concrete; the results in their research are high due to the marine transport of aggregates to Singapore from other countries. Adapting that research to this study, where no transport of aggregates is considered, results in values between 0.1 and 0.19 kg N-Eq/m^3 of ready-mixed concrete, which is lower than the results for this study.

Regarding ozone depletion—ODPinf, the results of this study are between 0.93×10^{-5} and 2.46×10^{-5} kg CFC^{-11}-Eq/m^3 of ready-mixed concrete. Cement production is the process with the highest contribution, with 53.18 to 85.10%. The second process is transport, contributing between 3.72 and 20%; this result varies depending on the distance between the concrete plant and the cement factory. According to previous literature, characteristic compressive strengths between 21 to 50 MPa are 6.93×10^{-6} to 9.2×10^{-5} kg CFC^{-11}-Eq/m^3 of concrete ready-mixed [50–52,54]; in this research, those values are similar for characteristic compressive strengths between 21 and 50 MPa, which is 1.50×10^{-5} to 2.23×10^{-5} kg CFC^{-11}-Eq/m^3 of ready-mixed concrete.

NO_x and VOC are the main substances that contribute to the photochemical oxidant formation—POFP impact category. These are mainly emitted during clinker production; hence, cement production is the critical process in this category, contributing from 46.73 to 82.43%. The POFP values for this study are between 0.50 and 1.19 kg NMVOC-Eq/m^3 of ready-mixed concrete; the result of all processes except for cement production remains between 0.20 and 0.30 kg NMVOC-Eq/m^3 of ready-mixed concrete. Adapting the study by Gursel & Ostertag [76], the result without aggregates' marine transport is 2.8 to 4 kg NMVOC-Eq/m^3 of ready-mixed concrete with OPC cement, a higher range than the ones calculated in this study.

Figure 4 shows the result of Particulate matter formation—PMFP, with values between 0.17 and 0.41 kg PM10-Eq/m^3 of ready-mixed concrete; the study by Gursel & Ostertag [76] has been adapted by removing the aggregate transport process, obtaining values between

1.70 and 2.25 kg PM10-Eq/m^3 of ready-mixed concrete; this is related to the low levels of PM in this study, focused on the production of Ecuadorian cement, the use of control equipment for the reduction and reuse of PM in the process, causing the PMFP to be lower than in the studies reviewed. The critical process of the impact category described is cement production, with contributions between 46.10 to 80.23%. As with most impact categories, the contribution increases as the cement content increases to improve the compressive strength of the concrete.

Fossil depletion—FDP was analyzed; the results obtained ranged from 22.55 to 60.25 kg oil-Eq/m^3 of ready-mixed concrete. The cement production process and admixture production are critical processes due to the consumption of thermal energy used in clinker production and organic chemicals. The contribution of cement and admixture production are between 42.28 and 67.09% and 10.17 and 23.02%, respectively. Both contributions increase due to the progressive consumption of these materials to improve concrete characteristic compressive strength.

Figure 5 shows a comparison of Global warming potential—GWP100 results between this research and previous results in the literature with compressive strengths of 20 to 70 MPa [49–52,54]. The study by Hossain et al. [48] of concrete in China analyzes compressive strengths between 59 and 70 MPa.

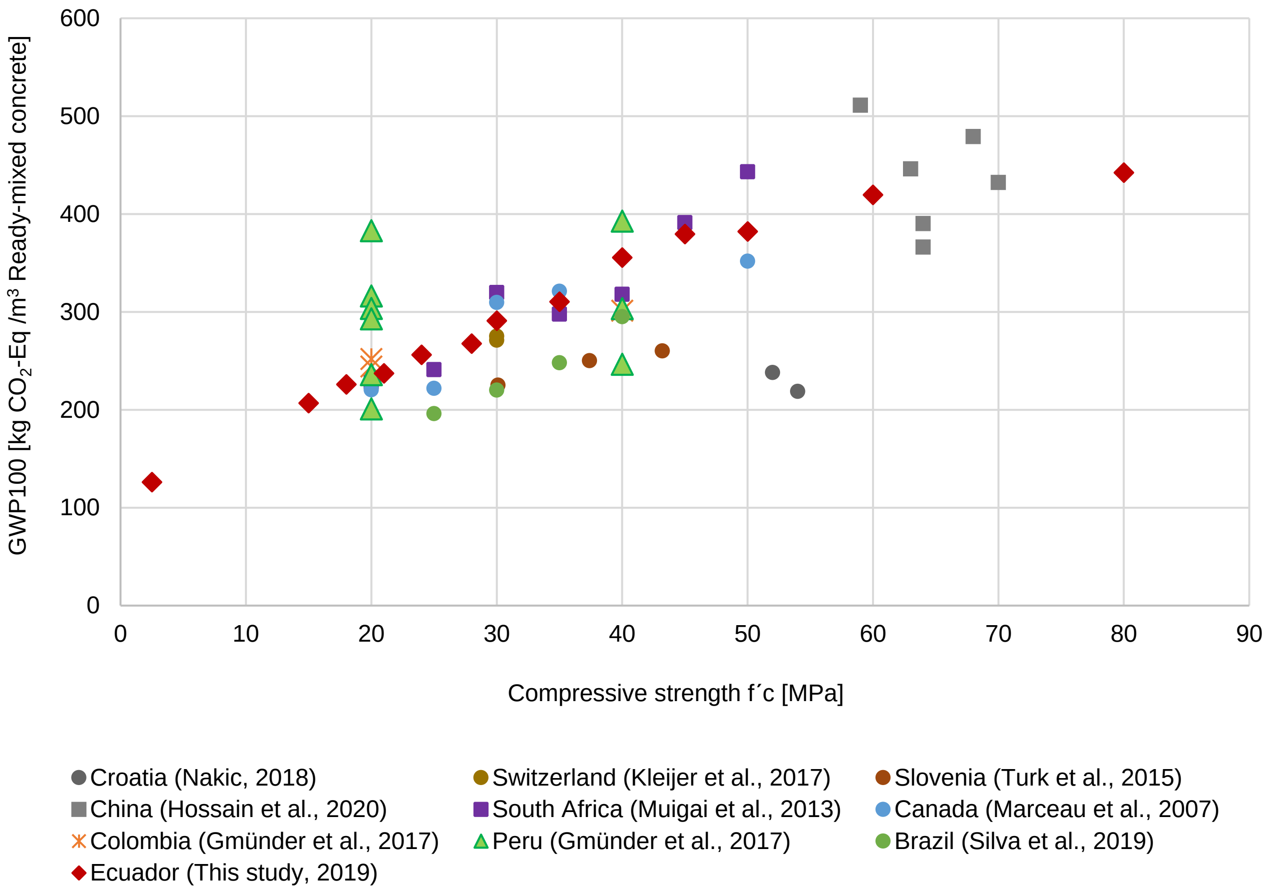

Figure 5. Global warming potential results of ready-mixed concrete in literature reviewed and this study.

The result of this study for Ecuadorian 21 MPa is 237.22 kg CO_2-Eq/m^3 of ready-mixed concrete. Studies with similar characteristic compressive strength (20 MPa) are from Peru, Colombia, Canada, and South Africa. The most similar values are those of Peru and Colombia, where pozzolanic cement concrete is used, with a differential between 0.60 to 6.19%. Concrete with limestone from Peru uses raw materials similar to those of Ecuador, with results between 55.68 and 66.20 kg CO_2-Eq/m^3 of ready-mixed concrete. OPC concrete shows a difference between 79.01 and 145.60 kg CO_2-Eq/m^3 of ready-mixed concrete due to the high clinker content of OPC.

The result for this study for 24 MPa is 256.08 kg CO_2-Eq/m^3 of ready-mixed concrete. Results in the literature for 25 MPa range from 221.85 to 240 kg CO_2-Eq/m^3 of ready-mixed concrete [49,51,52]. This study reports a higher value. The same authors report results between 246.5 and 392.74 kg CO_2-Eq/m^3 for 40 MPa ready-mixed concrete; this study result is 355.37 kg CO_2-Eq/m^3 of ready-mixed concrete, which is within the aforementioned results, the main differences between the studies are due to the components of the concrete, such as recycled material, fly ash, and slag.

For the compressive strength of 30 MPa, this study reports a value of 290.85 kg CO_2-Eq/m^3 of ready-mixed concrete. The results of Canada and South Africa are 6.44 and 9.91% higher, respectively. This study has a result of 310.30 kg CO_2-Eq/m^3 for 35 MPa ready-mixed concrete. This result is within the range of 297.56 to 320.97 kg CO_2-Eq/m^3 of ready-mixed concrete for Canada and South Africa [51,52]. The study for Slovenia presents values below the average of the rest of the countries due to the use of steel slags and foundry sands [49], in particular, 22.64 and 19.43% lower compared to the results for 30 and 35 MPa concretes of this study. The results for South Africa 45 MPa concrete are similar to this study's result with a difference of +11.71 kg CO_2-Eq/m^3 of ready-mixed concrete. For 50 MPa, studies from South Africa and Canada show results between 443.05 and 351.65 kg CO_2-Eq/m^3 of ready-mixed concrete; this study reports a higher value of 382.03 kg CO_2-Eq/m^3 of ready-mixed concrete.

Hossain et al. [48] analyzed the production of high compressive strength concrete in China with compressive strengths between 59 and 70 MPa. Concrete with characteristic compressive strengths between 59 and 64 MPa, with values of 390 at 511 kg CO_2-Eq/m^3 of ready-mixed concrete, is comparable to the 60 MPa concrete of this study with a result of 419.54 kg CO_2-Eq/m^3 of ready-mixed concrete, which is similar to 63 MPa results with +26.45 kg CO_2-Eq/m^3 of ready mixed concrete. The results of 68 and 70 MPa from the same study are close to the result for 80 MPa of this study, with +36.86 and −10.13 kg CO_2-Eq/m^3 of ready-mixed concrete, respectively. The influence of the use of materials, such as pozzolan and slag in the composition of Ecuadorian cement, was a determining factor in the reduction of GWP in concrete with high compressive strength compared to the literature reviewed.

4. Conclusions

The environmental performance of the production of clinker, cement, and concrete in Ecuador has been quantified using the life cycle assessment methodological framework. Input and output inventories of matter and energy have been generated for 62.8% of the cement industry and 55% of the concrete industry in Ecuador.

Environmental impacts of clinker production are mainly caused by gases generated in the combustion in clinker kilns, which is necessary to transform calcium carbonate into calcium oxide. This process becomes critical throughout the value chain of cement and concrete products in most of the established impact categories. The result for the environmental performance result of clinker of this study is similar to those found in the literature review in terms of GWP; other indicators such as TAP100 and FEP are reduced due to emissions control equipment, energy efficiency, and the Ecuadorian electricity mix. The environmental performance of clinker is necessary throughout the value chain of construction materials based on cement since this presents a baseline for the evaluation of environmental improvements at the cement production level. Improvement strategies that can be assessed include replacing clinker with alternative materials, such as pozzolan, slag, and fly ash, and the use of alternative fuels.

The environmental impact of the Ecuadorian cement industry has been determined using inventory data of cement types: GU, HE, and MH, used in conventional construction and the ready-mixed concrete industry. The results of impact assessment of cement based in Ecuador are at the lower range than those found in the literature due to the levels of additions in Ecuadorian cement and cement plant efficiency.

A range of compressive strengths has been covered in the quantification of the environmental performance of ready-mixed concrete from 2.5 MPa to 80 MPa; each conventional concrete used by the construction industry has been included in detail (18, 21, 24, 28, 30, 35, and 40 MPa).

Main strategies for improving the environmental profile of clinker, cement, and concrete should be focused on decreasing the environmental impact of the clinkerization process. For the clinker production system, this can be done by increasing the thermal efficiency and using fuels with lower environmental impacts. For the cement and the concrete systems, measures should be focused on reducing the content of clinker.

Cement and concrete environmental profiles obtained in this study are used to calculate the environmental performance of structural elements (columns, beams, foundations, etc.) and also structures, such as housing, buildings, and mega-infrastructure projects that use cement and concrete. The results of this study, based on local inventories, can be used in research on sustainable construction in Ecuador and countries with similar conditions for the production of materials and construction systems, such as the Latin American region. Using its GWP, it will be possible to determine reductions in CO_2 by materials. This makes it possible to quantify the current status and the improvements in compliance with SDG 13: Climate Action and seek solutions to make cities and human settlements inclusive, safe, resilient, and sustainable, according to SDG 11: Sustainable Cities and Communities.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings12030311/s1: Table S1: Summary of processes taken from ecoinvent database for LCIA Clinker in Ecuador; Table S2: Summary of processes taken from ecoinvent database for LCIA Cement in Ecuador; Table S3: Summary of processes taken from ecoinvent database for LCIA Concrete in Ecuador; Table S4: Life cycle inventories of clinker production in Ecuador (per ton of clinker); and Table S5: Life cycle inventories of concrete production in Ecuador (per m^3 of ready-mixed concrete).

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Data Availability Statement: All data generated or analyzed during this study are presented or can be reproduced using the life cycle inventories that are presented and references indicated.

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Conflicts of Interest: D.M.P works for a company that provided data for this study. A.D.R declares no conflicts of interest.

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