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Life Cycle Assessment of Concrete Production within a Circular Economy Perspective

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Abstract: The pursuit of sustainability in the construction and demolition (C&D) sector calls for effective decision-making strategies, both in terms of technical and environmental sustainability, capable of mitigating its huge demand for resources and emissions to the environment. The recycling of C&D waste is one of the potential solutions that could reduce the extraction of virgin materials as well as waste generation and landfilling. This study evaluates and compares, by means of the Life Cycle Assessment (LCA) approach, the production of concrete via five different mixtures made up of coarse natural aggregates (NA, primary, virgin materials), and coarse recycled concrete aggregates (RCA, recovered from previous uses). The present study assesses the environmental load of concrete production, by means of mixtures containing only coarse NA and mixtures with coarse RCA produced in fixed and mobile treatment plants, to be replaced with 30% and 100% of coarse NA by weight. The results point out that the use of coarse RCA in concrete mixtures provide greater energy savings and environmental advantages compared to the concrete with only coarse NA; the improvement increases up to a 100% replacement rate by weight of coarse NA with coarse RCA in the mixtures. In this case, the reduction of the impacts is significant for some impact categories such as freshwater ecotoxicity (−63.4%), marine ecotoxicity (−76.8%), human carcinogenic toxicity (−27.1%), human non-carcinogenic toxicity (−77.9%), land use (11.6%), and water consumption (−17.3%), while the total CED impacts decreases by about 10% and that of GWP by 0.4%. Results are discussed in light of the urgent need for advancing circular economy concepts and practices in the C&D sector and decrease the large use of primary resources (in particular sand and gravel). The replacement of NA with RA by weight could contribute to reducing the impacts of the C&DW management and disposal. For this to happen, further improvement of the quality of recycled aggregates is essential for their market development as well as dedicated policies and legislations.

Keywords: coarse natural aggregate; coarse recycled concrete aggregate; construction and demolition waste; life cycle assessment; circular economy

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1. Introduction

Construction and demolition (C&D) is a well-known sector generating high environmental impacts on the natural environment in terms of natural resource consumption and waste generation [1,2]. The conversion of C&D waste into recycled aggregates and their use, as an alternative to natural aggregates (NA), has increasingly attracted the interest of the research in this field, for its potential of reusing still valuable materials and avoiding their landfilling [1,3] as well as reducing the extraction of natural materials [4,5]. Several studies in the last decade have pointed out the impacts of the production of concrete based on aggregates from demolished concrete, namely recycled concrete aggregates (RCA) [6,7], and compared it with conventional concrete made of natural aggregates (NA) [8–10], considering different samples of NA and RCA and material size and how recycled aggregates (RAs) ultimately affect the physical properties of concrete and their durability [11–13]. The replacement of NA with RCA for the production of concrete can be total, substituting entirely their amount, or partial by using RCA in combination with NA in the mixtures [14,15].

A large number of studies adopted Life Cycle Assessment (LCA) as a method for assessing C&DW recycling [9,10,16] and comparing the environmental impacts of using RCA and NA in concrete production [17,18]. In that, LCA is also important in identifying the best environmentally friendly proportion of RCA in the mixtures [19] and evaluating, in general, the application of the CE principles in the C&DW sector [20] while also addressing the concept of material/product quality of input waste and recycled products [16]. LCA boundaries may be very different, depending on the goals of the study: studies may be performed within a "cradle to gate" perspective, when the focus is on the product as such [21] "cradle to grave" when the study also aims at including waste collection and disposal [6,17] and, finally, "cradle to cradle" when the goal is accounting for the environmental benefits of reintroducing the concrete waste in a new production and consumption cycle [20]. So far, the boundaries of several LCA studies analyzing the environmental impacts of concretes made of NA and RA or RCA have been mainly "cradle to gate" [7,15,18,19,21,22], while only a few were "cradle to cradle" [20]. RA or RCA are the output of recycling plants. These latter can be classified into two typologies: fixed and mobile recycling plants. The first ones are located in a specific site and cannot be moved easily [19]. They have a large primary crusher working together with a secondary or tertiary crusher as well as cleaning and sieving equipment for the production of high-quality aggregates [5]. Mobile plants are not fixed and can be moved from one demolition site to another. They have in general a crusher and sorting equipment and produce RA of lower quality by means of recycling C&DW in situ [5].

One of the earlier studies, Marinković et al. [7], found that the environmental impacts are a bit higher for RCA than conventional concrete due to the higher amount of cement in order for the recycled aggregate concrete (RAC) to have the same comprehensive strength and workability as conventional concrete. Further, Knoeri et al. [21] in the Swiss context, evaluated conventional and recycled concrete mixtures for different internal and external structural applications as well as leaner concrete. These authors considered the avoided disposal impacts due to the recycling and reuse of C&DW and the benefits of recycling of iron scraps generated in the process. The inclusion of the avoided impacts contributed to reducing the load of recycled concrete (RC) mixtures compared to the conventional concrete (CC) mixtures. Dealing with structural concrete, Knoeri et al. [21] showed that the mixtures with recycled concrete reduced by 30% the Ecoindicator 99 environmental impacts and ecological scarcity, while the RC and CC mixtures show similar performance for global warming potential because of the higher amount of cement in RC [21].

The literature search resulted in two studies which particularly addressed the topics dealt with in this study, namely the life cycle of coarse NA and coarse RCA and their use in concrete production, with a special focus on the environmental impacts of RCA treatment in both fixed and mobile plants. In this regard, Estanquiero et al. [22] compared three types of coarse aggregates for concrete such as coarse NA (extracted and processed) and coarse RA obtained from demolished concrete treated in mobile and fixed recycling plants, by applying the LCA approach. These authors considered three scenarios for the production of concrete: Scenario 1, where only NA is used; Scenario 2, which considers the use of coarse RCA treated in a fixed recycling plant; and Scenario 3, using coarse RCA produced in a mobile recycling plant. In all three scenarios they excluded the manufacturing process of concrete since the environmental impacts are assumed the same in all three scenarios.

In Scenario 1, the boundaries of the LCA includes the impacts of the extraction of the NA, their transport to the concrete plant, and the delivery of concrete to the construction site. Scenario 2 considers the transport of the aggregates from the demolition site to the fixed recycling plant, the impacts of the recycling stage, the transport of the derived RA to the manufacturing concrete plant, and the delivery of concrete to the construction site. Scenario 3 includes the impacts of the recycling stage performed by means of a mobile recycling plant, the transport of the derived RA to the concrete manufacturing plant, and the delivery of the concrete to the construction site. Their results show that Scenario 1 performs better than the other two for almost all the environmental categories of Eco-indicator 99 except for respiratory inorganics and land use. The environmental impacts of Scenario 1 are also lower, compared to Scenario 2 and Scenario 3, for all the considered midpoint indicators of CML Baseline 2000. Finally, Scenario 1 also shows lower impacts than Scenario 2 and Scenario 3 concerning CED indicators. The authors also performed a sensitivity analysis where they evaluated different alternatives concerning partial or total avoidance of fine RCA landfilling in Scenarios 2 and 3 for use in concrete production, in so improving the environmental impacts of some Scenario 2 and 3 categories. The impacts of the use of coarse RCA can be lower by 23% if all fine RCA are used instead of being landfilled. In this case, the adoption of selective demolition can assure the maximum recovery of the demolished concrete and its recycling for the production of RCA and is preferable compared to conventional demolition.

Colangelo et al. [19] further extended the analyzed processes in the LCA performed by Estanqueiro et al. [22], by also including the production process of concrete. In detail, as a representative case study of Italy, they evaluated and compared the impacts of concrete mixtures containing only coarse NA as well as coarse NA and coarse RCA with different RCA contents (30%, 50%, 70%, 100%). Moreover, they also compared single concrete mixtures of coarse RCA produced with both mobile and fixed recycling plants assuming for these latter plants the following transport routes: 10 km, 20 km, 30 km, 40 km, 50 km, and 60 km). They evaluated two models: model A, that does not consider the environmental benefits of avoided coarse NA production, and model B that considers the benefits of including coarse RCA in the mixtures and the consequent environmental savings of coarse NA production. Overall, their analysis comprised 29 scenarios of mixtures for concrete production. They showed the results in terms of the endpoint categories ozone depletion, human toxicity, and climate change. Their results highlight a constant trend, over the 29 analyzed scenarios of decreasing impacts from the scenarios with model A to model B. The impacts in the individual mixtures of concrete change according to the environmental benefits arising from reducing or avoiding at all the use of coarse NA and replacing them with coarse RCA produced in mobile and fixed recycling plants. The authors also performed a life cycle costing to understand which mixtures of concrete were the most preferable in economic terms. Their results showed that the coarse RCA100 mixture treated in mobile plants is the most economically sustainable since it avoids the purchase of coarse NA and has lower energy and transport costs compared to the coarse RCA 100 mixture treated in fixed plants.

This LCA further develops the previous assessment performed by Colangelo et al. [19] and aims to evaluate and compare, by means of LCA, the energy and midpoint impacts generated by the five concrete mixtures made of variable contents of coarse NA and coarse RCA treated in fixed and mobile plants (0%–30%–100%), maintaining for each mixture the same amount of the other components such as water and fine aggregates.

The CED impact assessment method [23] as well as the analysis of the environmental impacts have been integrated by adopting the ReCiPe MidPoint impact assessment method [24], further expanded showing the midpoint impact indicators. The different impact assessment methods used in this study are the main novelty compared to the LCA performed by [19] where the ReCiPe EndPoint impact assessment method [24] has been used. Moreover, this study interpreted the results in light of the need for drawing attention to other impacts rather than climate change such as land use.

2. Materials and Methods

The materials composing the selected concrete mixtures evaluated in this study are presented in Section 2.1, while the LCA model adopted is described in Section 2.2 throughout the four stages of its methodological framework as envisioned in the standard ISO 14044/2006 [25].

2.1. Analyzed Mixtures of This Study

Table 1 shows the input contained in each one of the concrete mixtures considered in this study and their quantities in relation to 1 tonne of concrete. More details about the mixtures and their content are presented in Sections 2.2.1 and 2.2.2.

Table 1. Materials contained in each one of the five selected mixtures and share of RCA compared to the total amount of the mixtures.

Mixture	Coarse Natural Aggregates (kg/Tonne)	Coarse Recycled Concrete Aggregates (% of the Total Amount of the Mixture)	Coarse Recycled Concrete Aggregates (kg/Tonne)	Fine Aggregates (kg/Tonne)	Ordinary Portland Cement (kg/Tonne)	Water (kg/Tonne)	HRWR * (%OPC)	Total Mass (kg/Tonne)
CRCA0	383.03	0	0	380.85	143.93	89.89	1.5	997.72
CRCA30-60 km (fixed plant)	265.40	30%	113.68	376.77	149.01	100.69	1.5	1005.57
CRCA30-30 km (mobile plant)	265.40	30%	113.68	376.77	149.01	100.69	1.5	1005.57
CRCA 100-60 km (fixed plant)	0	100%	377.52	375.45	150.72	101.85	1.5	1005.55
CRCA100-30 km (mobile plant)	0	100%	377.52	375.45	150.72	101.85	1.5	1005.55

Notes: * HRWR: High Range Water Reducer (superplasticizer).

2.2. Life Cycle Assessment

This section provides an overview of the LCA model adopted taking into account the standard ISO 14044/2006 [25]. The latter standard points out the required characteristics of a LCA study and gives instructions on how to conduct the latter in all the four stages. Next, each one of the stages are briefly introduced and described in relation to this case study.

2.2.1. Goal and Scope Definition

This stage defines the goal of an LCA study and other important elements (boundaries of the system, FU, etc.), and for this reason, it is a central phase in an LCA because it determines the model of LCA that will be adopted. However, both the aim and the boundaries of the investigated system can be modified during the LCA as data are collected and new information becomes available [26].

The goal of the present LCA is evaluating and comparing the impacts generated by five concrete mixtures, consisting of variable contents of coarse NA and coarse RCA (0%–30%–100%) as considered in Colangelo et al. [19]. Coarse NA and coarse RCA as materials are also compared and individually analyzed to assess the main hotspots in their lifecycle. The five mixtures have the same amounts of other components such as water and fine aggregates.

Therefore, this LCA analyses the ecological footprints of the following mixtures:

- NA = 100%-CRCA = 0%. Fine aggregates (from rivers) and coarse NA (from quarries) are used. This corresponds to the mixture CRCA0;
- NA = 70%-CRCA = 30% recycled in a mobile plant. This mixture consists of coarse and fine NA and coarse RCA. This is the mixture CRCA 30-30 km mobile plant;
- NA = 70%-CRCA = 30% recycled in a fixed plant. This mixture consists of coarse and fine NA and coarse RCA. This is the mixture CRCA 30-60 km fixed plant;
- NA = 0%-CRCA = 100% recycled in a mobile plant, consists of only CRCA. This mixture is CRCA 100-30 km mobile plant;

- NA = 0%-CRCA = 100% recycled in a fixed plant, only CRCA are used. This mixture is CRCA100-60 km fixed plant.

In the mixtures NA = 70%-CRCA = 30% and NA = 0%-CRCA = 100%, it is assumed that coarse RCA is replaced with 30% and 100% fine and coarse NA by weight.

The reasons for this study are to provide an appropriate informative basis about the possibility to recover construction waste and reuse them in the construction sector.

The scope may require additional information. First of all, Figure 1 summarizes the processes considered in this LCA such as the production of cement and NA, the withdrawal of water and the process of recycling of the C&DW for the production of coarse RCA, as well as their transport to the plant for the production of concrete.

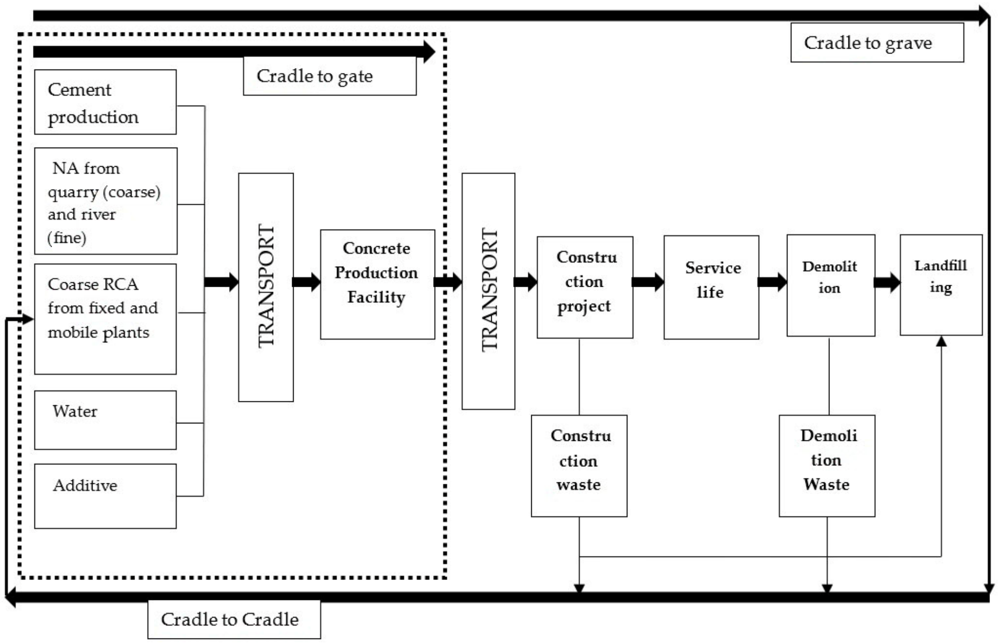

Figure 1. Processes included in the present life cycle assessment study (cradle to gate) within the framework of the entire life cycle of a construction project (cradle to cradle). Own elaboration of the authors.

The functional units chosen in this study are:

1 tonne of coarse NA and 1 tonne of coarse RCA used in the concrete mixtures (coarse RCA 30 and coarse RCA 100);

1 tonne of coarse NA and 1 tonne of coarse RCA considered individually in order to compare their impacts to identify the main hotspots in their lifecycle.

The data about cement and additive production processes and water come from Ecoinvent 3.8. The data of cement only considers the production stage in the manufacturing enterprise and excludes the haulage of the required materials utilized for its production.

The assumptions made for the LCA model of this study are the following:

- The C&D waste used as input only consists of the concrete fraction without other types of materials (e.g., mixed C&DW, metals, plastic, wood). This hypothesis assumes that, given the high quality of the input concrete, the mobile plant and the fixed plant provide the same quality of coarse RCA. All the mixtures are characterized by similar mechanical resistance and workability;
- The mobile treatment unit is in the same place of the demolished building/infrastructure project. This hypothesis is in line with the current practice, as the proximity with the demolition site is one of the main advantages of the mobile plants;
- The haulage from the fixed/mobile plant to the concrete manufacturing plant considers the same distance of 30 km;

- An average distance of 30 km is assumed from the demolition place to the fixed recycling unit;

A further assumption regards the amount of C&DW not treated and included in the CRCA0 and CRCA 30 concrete mixtures that are disposed of in a landfill. The C&DW disposed of are 377.52 kg (CRCA0) and 263.84 kg (CRCA 30), respectively. Instead, in the case of CRCA100 mixture all the C&DW are treated (377.52 kg) for the preparation of the concrete mixture.

In conclusion, the present study evaluates and compares the impacts of five mixtures containing different percentages of coarse RCA in replacement of coarse NA, treated in industrial plants, respecting the distances indicated in the assumptions.

Such analysis has been carried out according to a circular economy framework and a cradle to gate LCA, in order to decrease the local and global impacts of construction and demolition waste and provide global opportunities for economic savings and potentially new jobs.

2.2.2. Life Cycle Inventory

The ISO 14044/2006 [25] standard states that this stage involves "*the compilation and quantification of inputs and outputs for a product throughout its life cycle*". The input and outputs in the inventory can be reconducted to the following elements: energy and raw materials consumption; airborne, waterborne, and terrestrial emissions; and solid waste and other releases to the environment [14].

In practice, the inventory consists in the development of a flow diagram that depicts all of the steps or sub-processes within the system boundaries and the product flows to or from other systems that are not included [25,27]. The definition of the procedure for collecting the data, the activities of collection and recording of the essential data for the LCA study, and their analysis also characterize this stage [14].

This LCA utilizes different type of data. Most of the latter have been collected from Ecoinvent Database v. 3.8 and are related to the production of FA, coarse NA, cement and additive. The transport of FA and coarse NA, assumes average distances considered by previous studies [28–30]. The features of the sub-processes are summarized in Table 2.

Table 2. Summary of the input composing each analyzed mixture and data about their subprocesses.

	Main Input and Their Subprocesses	**FU**
1.	Fine Aggregates. Ecoinvent 3.8: • Sand [GLO] 1.04 tonne; • Transport, freight, lorry 16–32 metric ton, EURO5 [GLO]. Distance to the concrete facility: 20 km	1 tonne
2.	Coarse Natural Aggregate.; Ecoinvent 3.8: • Gravel, crushed [RoW], market for gravel: 1.04 tonne; • Transport, freight, lorry 16–32 metric ton, EURO5 [GLO]: Distance to the concrete facility: 20 km;	1 tonne
3.	Coarse Recycled Concrete Aggregate (CRCA) (Fixed treatment plant). Ecoinvent 3.8: • Diesel, burned in building machine [GLO]: 8.25 MJ/t. • Electricity medium voltage (IT): 1.13 kWh/t. • Steel, unalloyed [GLO] 0.02 kg/t • Transport, freight, lorry 16–32 metric ton, EURO5 [GLO]. Distance from the demolition site to the fixed plant is 30 km while to the concrete facility is 30 km (total 60 km).	1 tonne
4.	Coarse Recycled Concrete Aggregate (CRCA) (Mobile treatment plant). Transport to the concrete facility: 30 km. Ecoinvent 3.8: • Diesel, burned in building machine [GLO]: 21.13 MJ/t. • Steel, unalloyed [GLO]: 0.02 kg/t. • Water, unspecified natural origin (IT): 1.56 l/t = 1.56 kg/t. • Transport to the concrete facility: 30 km.	1 tonne

Table 3 summarizes the data about the consumption of the main input (electricity, diesel, water, steel) in both fixed and mobile plants reported by the literature. This study considered in particular the consumption of electricity, diesel, and water by Borghi et al. [29].

Table 3. Consumption of energy and other input in recycling plants, from the literature.

Input	Recycling Mobile Plants	Recycling Fixed Plants	Reference
Electricity		1.13 kWh/tonne 1.002 kWh/tonne	Borghi et al. [29] Blengini and Garbarino [30]
Diesel	0.64 L/tonne 0.688 L/tonne	0.25 L/tonne 0.680 L/tonne 23.46 MJ/tonne	Borghi et al. [29] Blengini and Garbarino [30] Estanquieiro et al. [22]
Water	1.56 L/tonne	6.7 kg/tonne	Borghi et al. [29] Blengini and Garbarino [30]
Steel	0.02 kg/tonne	0.02 kg/tonne 0.0105 kg/tonne	Borghi et al. [29] Blengini and Garbarino [30]

Further data about concrete production, collected by the Ecoinvent 3.8 database [31] are:

- Cement Portland (Europe without Switzerland): A quantity ranging from 143.94/tonne to 150.73 kg/tonne has been considered for all the five mixtures;
- Water, unspecified natural origin (IT): A quantity ranging from 89.90 kg/tonne to 101.85 kg/tonne has been assumed for the five mixtures;
- Additive (Superplasticizer for concrete): the quantity considered is 1.5% of the amount of cement;
- Electricity medium voltage (Italy): 1 m^3 of concrete requires 14 kWh of electricity [19];
- Inert Waste (Europe without Switzerland) is the subprocess used for the disposal of C&DW in landfill.

2.2.3. Life Cycle Impact Assessment (LCIA)

In this stage, input as well as output flows of the inventory are attributed to specific impact categories (classification), and the potential impacts of the system under investigation are quantified (characterization) by means of impact assessment methods. The LCA was carried out using SimaPro version 9.1.1, while the impacts have been calculated considering the cumulative energy demand method, CED [23] and ReCiPe [24] with indicators at Midpoint level.

3. Results

3.1. Life Cycle Energy Impacts (CED) of the Analyzed Five Mixtures for Concrete Production

Table 4 shows the characterized CED impacts of the five concrete mixtures. It is possible to highlight that the total CED impacts slightly decrease (by about 10.23%) shifting from the mixture CRCA-0 (986.67 MJ) that does not include the use of CRCA to the mixture CRCA-100-Mobile plant (885.75 MJ) where only CRCA are used as well as the recycling which is performed by means of a mobile plant. However, both CRCA-100 mixtures have a lower total CED than the CRCA-0 since the CRCA-100-30 km fixed plant generate a contribution of 913.93 MJ. It is interesting to note that in both CRCA-100 mixtures, the energy costs of landfilling are avoided as the mixtures are composed of all CRCA, which explains the reason of the reduction of CED impacts. Table 4 also shows that the manufacturing of cement (590.59 MJ) accounts for about 60% of the impacts to the overall CED in CRCA-0 mixture. The relative weight of cement to the total CED impacts increases in the two CRCA-100 mixtures to 619.52 MJ.

Table 4. Characterized induced CED impacts of the five typologies of concrete mixtures analyzed in this LCA study.

Mixtures for Concrete Production	Unit/Tonne	Total CED Impacts	Fine NA	Cement, Portland	Coarse NA	Coarse RCA	Plasticizer for Concrete	Transport	Electricity, Medium Voltage {IT}	Inert Waste Landfilling
CRCA-0	MJ	986.67	91.74	590.89	121.35	0	72.92	-	49.78	60.00
CRCA-30-60 km-fixed plant	MJ	970.09	87.68	590.89	81.21	11.32	72.92	34.57	49.78	41.73
CRCA-30-30 km-mobile plant	MJ	961.91	87.68	590.89	81.21	3.14	72.92	34.57	49.78	41.73
CRCA-100-60 km-fixed plant	MJ	913.93	90.55	619.52	0	38.97	76.45	36.24	52.19	-
CRCA-100-30 km-mobile plant	MJ	885.75	90.55	619.52	0	10.80	76.45	36.24	52.19	-

The high contribution of cement can be also ascertained in Figure 2 which shows the characterized CED impacts over the five mixtures and the contribution in each one of the mixtures of the different input.

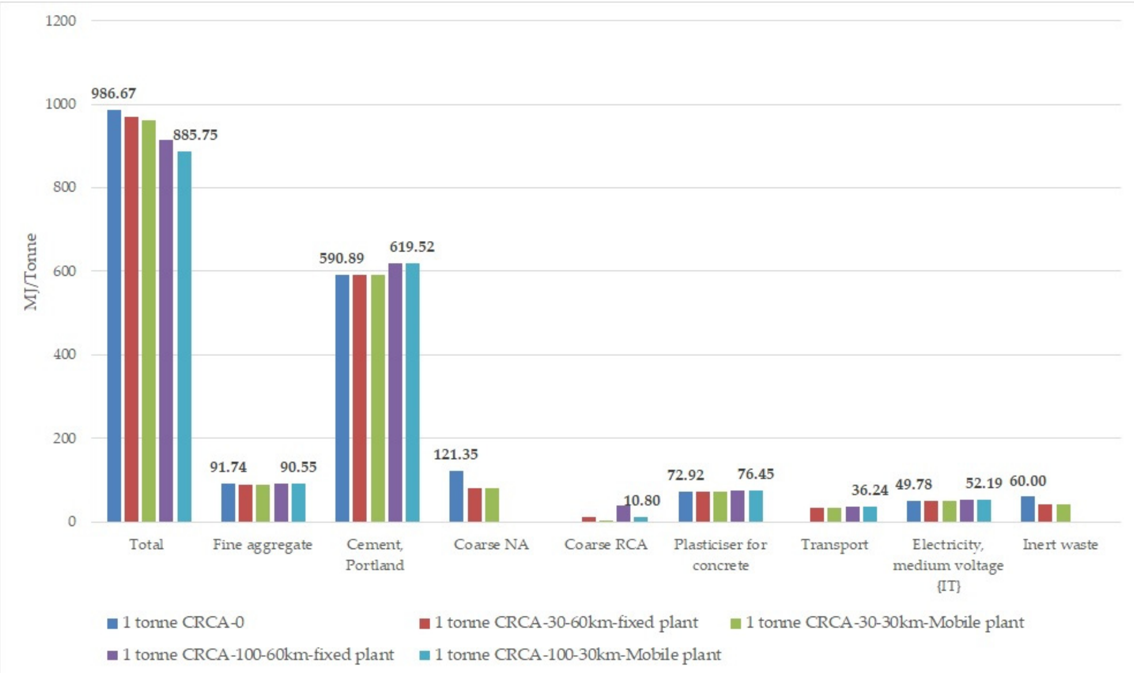

Figure 2. CED impacts of the different concretes (from left to right: total, four typologies produced, inputs).

Figure 3 shows the characterized impacts related to coarse NA and coarse RCA. The CRCA produced in a mobile plant shows the lowest CED impacts, requiring 28.60 MJ compared to 317.37 MJ associated to the production of coarse NA as well as of coarse RCA in a fixed recycling plant (103.23 MJ). Figure 3 also shows that for the production of 1 tonne of the coarse NA, the highest impacts are due to the gravel crushing (262.53 MJ) compared to their transport (54.85 MJ). In 1 tonne of coarse RCA, produced in a mobile plant, the highest energy impacts come from the use of diesel in the mobile plant (28.25 MJ), while in 1 tonne of coarse RCA treated in a fixed plant, the transport has the highest impacts (82.27 MJ).

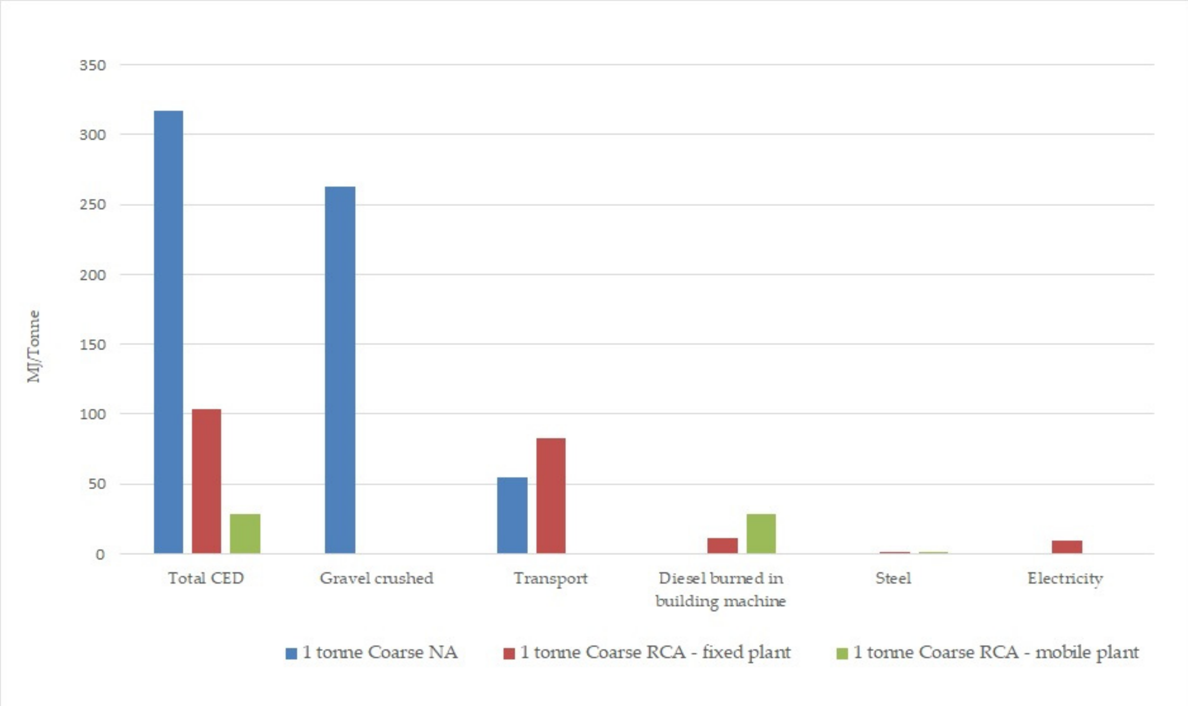

Figure 3. Total and disaggregated CED impacts of 1 tonne of coarse NA as well as 1 tonne of coarse RCA (produced in mobile and fixed recycling plants).

3.2. Life Cycle Environmental Impacts of the Analyzed Five Mixtures for Concrete Production

Table 5 shows the contribution to each one of the midpoint impact categories generated by the five mixtures. Overall, the impacts decrease from the mixture CRCA-0 (that has the highest impacts) to the other four achieving the lowest values in the mixture CRCA-100-mobile plant. The only exception is about the impact category "Mineral resource scarcity" where the value for the CRCA-100-60 km-fixed plant is higher (0.78 kg Cu eq/m^3) than the mixture CRCA-0 (0.77) kg Cu eq/m^3. As can be seen from the last column of Table 5, there is a little difference among the mixtures with regard to global warming potential, where the production of concrete by using the mixture CRCA-0 generates a contribution of 144.35 kg CO_2 eq, while the CRCA-100 mobile plant releases 143.77 kg CO_2 eq, 0.4% lower compared to CRCA-0. The contribution of CRCA-100 mobile plant is much lower than the CRCA-0 for the impact categories freshwater ecotoxicity (−63.4%), marine ecotoxicity (−76.8%), human carcinogenic toxicity (−27.1%), human non-carcinogenic toxicity (−77.9%), land use (11.6%), and water consumption (−17.3%).

Table 6 shows the potential environmental impacts of the life cycle of 1 tonne of coarse NA and 1 tonne of coarse RCA produced in mobile and fixed recycling plants. The impacts are higher for the life cycle of NA in all the impact categories. With regard to global warming potential, the life cycle of 1 tonne of coarse NA releases 18.53 kg CO_2 eq, while 1 tonne of coarse RCA produced in fixed and mobile plants releases 6.22 and 1.91 kg CO_2 eq, respectively. Coarse NA and coarse RCA are among the main components of the five mixtures investigated in this study. This means that a decrease of the total impacts will mainly depend on the decrease in these major components.

Table 5. Characterized midpoint environmental impacts associated to the five mixtures for concrete production.

Impact Category	Unit/Tonne	CRCA-0	CRCA-30-30 km Mobile Plant	CRCA-30-60 km-Fixed Plant	CRCA-100-60 km-Fixed Plant	CRCA-100-30 km-Mobile Plant	CRCA-0/CRCA-100-30 km-Mobile Plant
Global warming potential	kg CO_2 eq	144.35	143.28	143.76	145.39	143.77	−0.4%
Stratospheric ozone depletion	kg CFC11 eq	0.00	0.00	0.00	0.00	0.00	−11.0%
Ionizing radiation	kBq Co-60 eq	9.56	9.18	9.22	8.59	8.43	−11.8%
Ozone formation, Human health	kg NO_x eq	0.31	0.30	0.30	0.28	0.28	−8.4%
Fine particulate matter formation	kg PM2.5 eq	0.11	0.10	0.10	0.10	0.10	−10.3%
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.31	0.30	0.30	0.29	0.29	−8.4%
Terrestrial acidification	kg SO_2 eq	0.28	0.27	0.27	0.26	0.26	−7.7%
Freshwater eutrophication	kg P eq	0.02	0.02	0.02	0.02	0.02	−11.6%
Marine eutrophication	kg N eq	0.00	0.00	0.00	0.00	0.00	−5.6%
Terrestrial ecotoxicity	kg 1,4-DCB	339.34	343.72	354.12	323.63	287.83	−15.2%
Freshwater ecotoxicity	kg 1,4-DCB	4.50	3.63	3.64	1.69	1.64	−63.4%
Marine ecotoxicity	kg 1,4-DCB	45,630.02	35,044.85	35,168.17	11,032.96	10,608.42	−76.8%
Human carcinogenic toxicity	kg 1,4-DCB	254.58	233.36	234.82	190.61	185.57	−27.1%
Human non-carcinogenic toxicity	kg 1,4-DCB	40,174.34	30,706.73	30,806.21	9239.88	8897.41	−77.9%
Land use	m^2a crop eq	4.12	3.93	3.96	3.74	3.64	−11.6%
Mineral resource scarcity	kg Cu eq	0.77	0.76	0.76	0.78	0.77	0.04%
Fossil resource scarcity	kg oil eq	18.17	17.77	17.94	16.85	16.27	−10.5%
Water consumption	m^3	1.07	0.98	0.99	0.89	0.88	−17.3%

Table 6. Characterized midpoint impacts of 1 tonne of coarse NA and 1 tonne of coarse RCA obtained in both fixed and mobile plants.

Impact Category	Unit/Tonne	Coarse NA	Coarse RCA Fixed Plant	Coarse RCA Mobile Plant
Global warming potential	kg CO_2 eq	18.53	6.22	1.91
Stratospheric ozone depletion	kg CFC11 eq	0.00	0.00	0.00
Ionizing radiation	kBq Co-60 eq	3.54	0.60	0.16
Ozone formation, Human health	kg NO_x eq	0.09	0.03	0.02
Fine particulate matter formation	kg PM2.5 eq	0.04	0.01	0.01
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.09	0.03	0.02
Terrestrial acidification	kg SO_2 eq	0.08	0.02	0.01
Freshwater eutrophication	kg P eq	0.01	0.00	0.00
Marine eutrophication	kg N eq	0.00	0.00	0.00
Terrestrial ecotoxicity	kg 1,4-DCB	198.11	97.33	2.51
Freshwater ecotoxicity	kg 1,4-DCB	0.72	0.13	0.01
Marine ecotoxicity	kg 1,4-DCB	5302.43	1198.85	74.33
Human carcinogenic toxicity	kg 1,4-DCB	136.98	19.98	6.65
Human non-carcinogenic toxicity	kg 1,4-DCB	4298.79	953.35	46.22
Land use	m^2a crop eq	1.05	0.29	0.03
Mineral resource scarcity	kg Cu eq	0.08	0.01	0.00
Fossil resource scarcity	kg oil eq	5.90	2.15	0.62
Water consumption	m^3	0.42	0.02	0.00

Focusing on the results of the production of 1 tonne of coarse NA, the highest impacts are generated during the gravel production obtained by crushing, compared to the transport stage as shown in Figure 4.

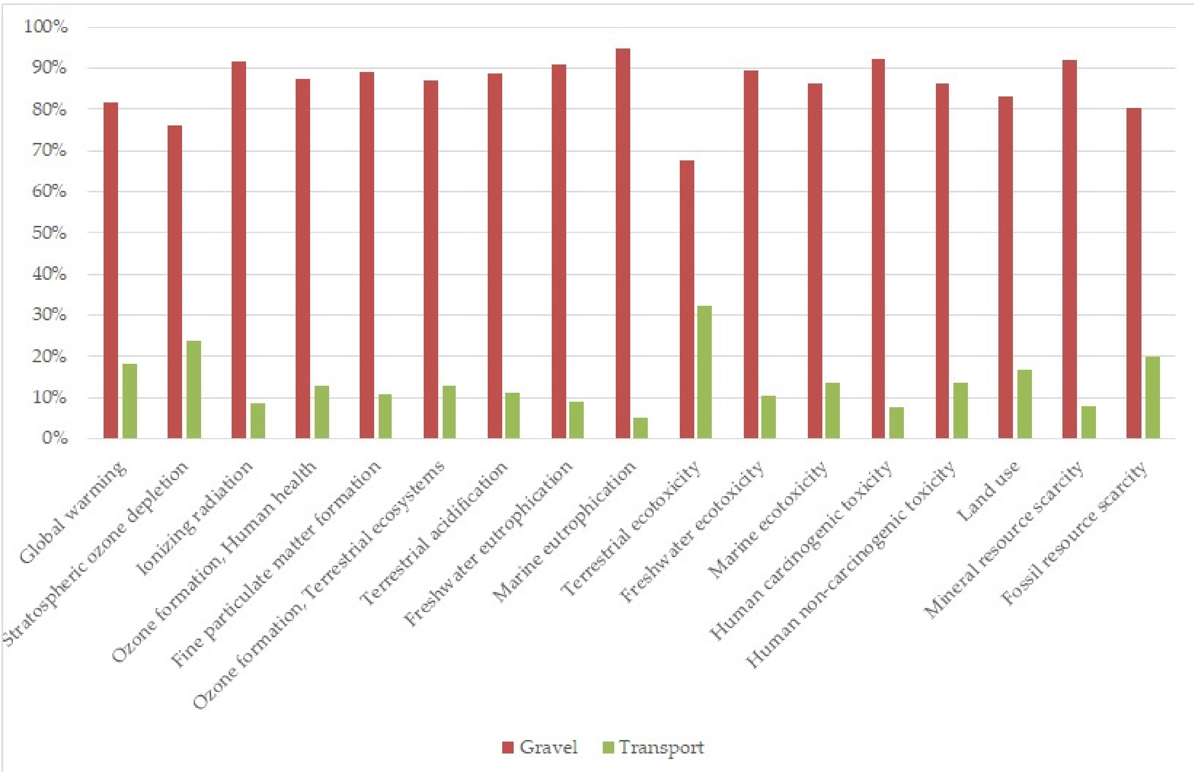

Figure 4. Percentage contribution of inputs to the total midpoint impacts of coarse NA production.

Figure 5 shows that a critical stage is that of haulage of C&DW from the demolition site to the fixed recycling plant, accounting, e.g., in the global warming potential category, for about 80% of the total impacts.

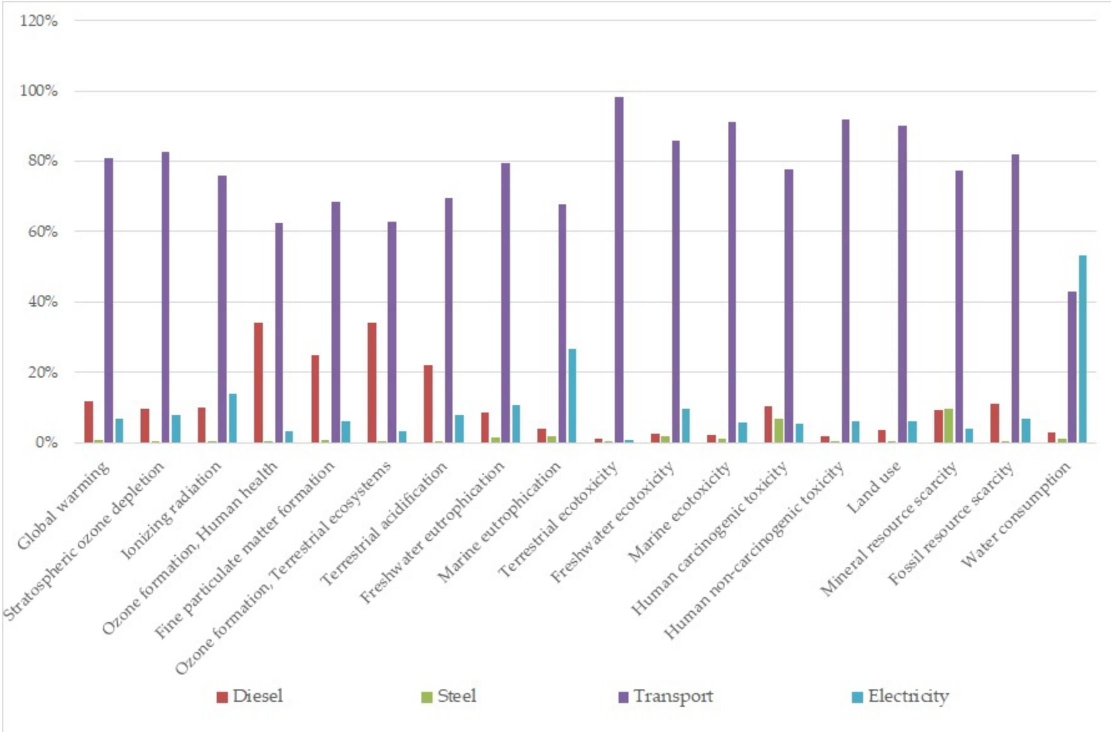

Figure 5. Percentage contribution of inputs to the total impacts, when treating 1 tonne of coarse RCA in a fixed recycling plant.

Finally, Figure 6 shows the impacts to the treatment of coarse RCA in a mobile plant. The highest contribution to the total is due to the use of diesel for the operativity of the recycling plant to obtain the coarse RCA.

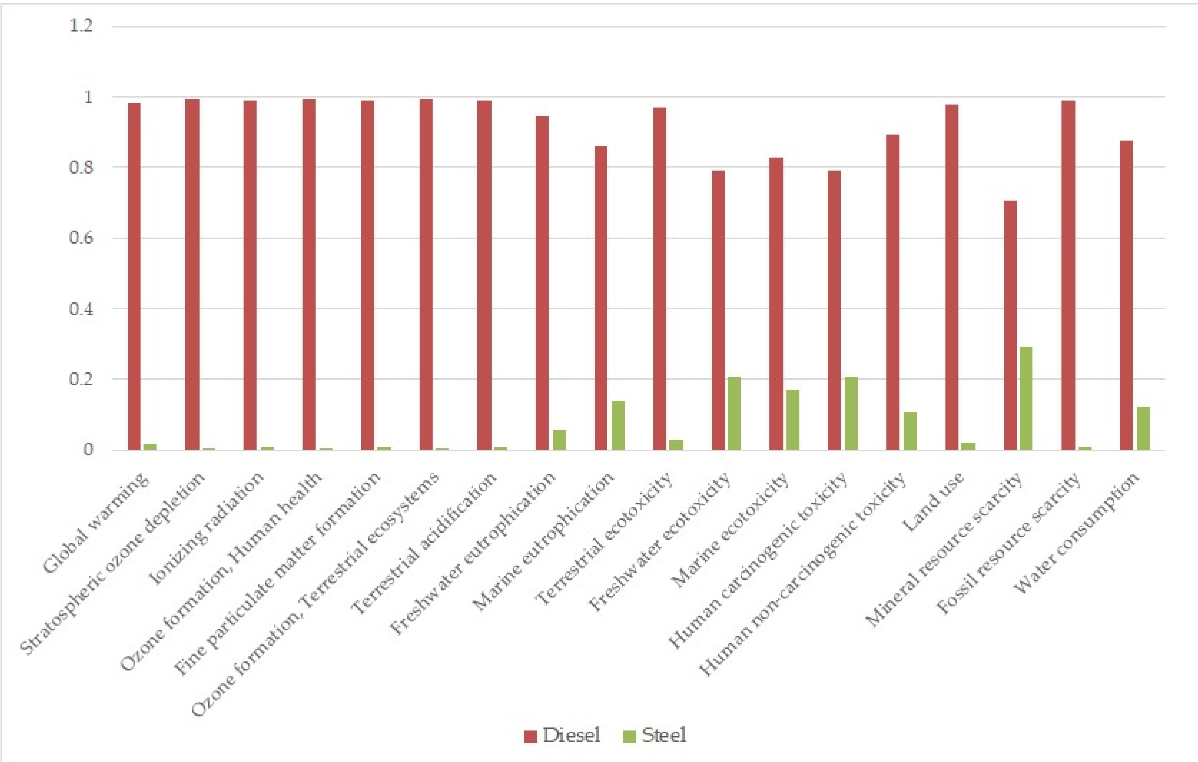

Figure 6. Percentage contribution of inputs to coarse RCA treatment in a mobile recycling plant.

4. Discussion

4.1. Environmental Performances of Concrete Mixtures Made of Coarse Natural and Recycled Concrete Aggregates

The results show that the energy and environmental impacts caused by the five mixtures considered (CRCA-0, CRCA-30 mobile plant and fixed plant, CRCA-100 mobile plant and fixed plant), are affected by the quantity of CRCA used in the mixtures. In fact, the energy and environmental impacts are reduced by adding higher proportions of CRCA in the concrete mixtures. However, the decrease varies across the impact categories. The total CED reduces from the mixture CRCA-0 compared to the CRCA-100-mobile plant by about 10%. Further, with regard to the environmental midpoint impacts, the decrease in GWP is not very significant, while shifting to the different mixtures composed of CRCA. Instead, for other impact categories (freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, and water consumption), the reduction is remarkable.

Concerning the comparison of the life cycle of 1 tonne of coarse NA and coarse CRCA treated in fixed and mobile recycling plants, the energy and environmental impacts are significantly lower than those associated with 1 tonne of coarse NA and, respectively, by 67.47% compared to the CRCA fixed plant and 89.69% for the CRCA mobile plant.

The comparison with existing LCA studies is not easy since there are differences in the concrete mixtures considered and the fraction of CRCA included as well as other inputs used in the mixtures.

Marinković et al. [7], one of the earlier LCA studies on the topic, considered the production and transport of the aggregates (both coarse NA and CRCA) and cement and the production of concrete and transport of concrete from the concrete plant to the construction site as system boundaries. Just as a comparison, the energy impacts of the scenario 1 were 1570.42 MJ/m^3 of concrete made of coarse NA, while the GWP impacts were 307.61 kg CO_2 eq/m^3. The energy use impacts were 1613.02 MJ/m^3 of concrete made of CRCA, while the GWP impacts were 319.63 MJ/m^3. The LCA study conducted by Ding et al. [20] evaluated four scenarios for concrete production containing only NA Scenario A; 50% NA and 50% RCA (Scenario B); only RCA (Scenario D), as well as two improved scenarios, both for the concrete made of 50% of RCA (Scenario C) and 100% of RCA (Scenario E). Their results show that the GWP impacts are 403.42 kg CO_2 eq/m^3 of concrete (Scenario A), increasing to 405.86 kg CO_2 eq/m^3 (Scenario B) and 406.49 kg CO_2 eq/m^3 (Scenario D). CED impacts are 1207 MJ/m^3 of concrete in the Scenario A, increasing to 1214.11 MJ/m^3 in Scenario B and 1215.25/m^3 in Scenario D. Finally, the CMR (consumption of primary mineral resources) indicator seems more favourable in the scenarios with concrete made of RCA both in the mixture with 50% and 100% of them. In Scenario A, the CMR is 2437 kg/m^3 of concrete, while in Scenario B, the CMR decreases to 1925.60 kg/m^3 of concrete to finally reach 1366.20 kg/m^3 of concrete in Scenario D. In this study, on the basis of the assumed transport distances, the environmental benefits can be obtained only for the CMR indicator compared to GWP and CED.

Finally, Estanqueiro et al. [22], who assessed the impacts of the life cycle of concrete from coarse NA (Scenario 1), coarse RCA treated in both fixed (Scenario 2), and mobile (Scenario 3) recycling plants, show that GWP (100) is 15.4 kg CO_2 eq (Scenario 1), while it is 24.4 kg CO_2 eq (Scenario 2) and 20.5 kg CO_2 eq (Scenario 3). Finally, total CED is 246.24 MJ (Scenario 1), 450.75 MJ (Scenario 2), and 386.49 MJ (Scenario 3).

4.2. Impacts of Results for Future Policies

This study found that concrete mixtures containing proportions of coarse RCA have lower environmental impacts than concrete mixture produced by using only coarse NA. In the comparison among the mixtures, it is important to call attention to GWP and energy consumption as well as to the environmental impacts generated by the use of primary natural resources and land use [28] with benefits in terms of reduced damages to existing habitats and ecosystems [5,32]. As an environmental category, “land use” refers to relative species loss due to local land use, land occupation, land transformation, and land relaxation processes [24]. The mixture CRCA-100-30 km mobile plant shows a lower contribution to land use that decreases by 11% compared to the mixture CRCA-0.

This result is particularly relevant in the light of the annual production of concrete in Italy the year 2021 that amounted to 35,796,225 m^3 (data for the ready-mix concrete) [33] and the global production of concrete the year 2020 that amounted to 14.0 billion of m^3 [34]. In Italy, in the year 2021, a survey of the companies producing concrete (representing 25% of the national production of ready mixed concrete) highlighted that, in the year 2021, they used the following for the production of concrete:

- 16,515,652 tonnes of natural aggregates;
- 43,241 tonnes of recycled aggregates;
- 21,344 tonnes of industrial aggregates.

These data show that the market of recycled aggregates is still underdeveloped, while the report also indicates that their use is still not uniform in the country across regions. It is important to underline that Federbeton Confindustria, an association of Italian producers of cement and concrete, underlines that the recycling potential of C&DW is very interesting for the ready-mix concrete sector, but the current characteristics of such waste and the practices adopted for their processing including the demolition techniques, severely limit the quality and technical characteristics of the recycled aggregates [33,35]. This prevents the advancement of the transition to CE in the sector, and the opportunities of reducing the impacts to the utilization of virgin materials consumption and waste generation [36].

With regard to land use category (ReCiPe, 2016) [24], it is interesting to deepen on its impact pathway, which contributes to the loss of species and damages to the ecosystems. The cause is the change in land cover as would happen with the extraction of primary aggregates used in construction such as sand and gravel. The changes in land use and land cover directly affect the original habitat and the original species composition leading to both loss of habitats and potentially to the disappearance of fractions of species, since land use change makes habitats unsuitable for the original species [24].

Several UNEP reports [37,38] highlight the unsustainable extraction levels of sand and gravel and other materials mined worldwide. Sand and gravel account for 65 to 85% of all materials mined globally. These essential ingredients for the production of cement and concrete originated by millennial erosive processes [39]. The volume extracted of sand and gravel each year amounts to 50 billion tonnes. This activity has significant impacts on rivers, deltas, and coastal and marine ecosystems resulting in the loss of land by means of river erosion, reduction of the water table, and the amount of sediment supply [37]. The high impacts due to the utilization of sand and gravel on the environment are still not properly taken into account by policy makers as well as are unknown by the general public. For these reasons, [38] underlines the urgency of considering, in particular, sand as a strategic resource which extraction and use should be rethought by adopting better circular and sustainable management practices and solutions. In this regard, the UNEP [38] suggests 10 valuable recommendations, summarized in Table A1 of the Appendix A.

4.3. Circular Economy, Life Cycle Assessment, Natural and Recycled Aggregates

The implementation of CE principles in the C&D activities entails the need for designing and maintaining the environmental value of materials and products as long as possible as well as limiting the use of hazardous waste and impacts to the environment. Therefore, in the CE model, tools such as the LCA performed in this study as well as other methods such as Material Flow Accounting [40] and Emergy Accounting [41], and their related indicators are important to show the environmental value of both virgin and recycled materials that is not fully considered by their market value. The Ellen Mac Arthur Foundation [42] underlines the focus of CE model in minimizing the environmental negative externalities by means of the design of products and materials and the attention to provide positive regenerating benefits to natural systems.

The case of sand and gravel, evidenced above, which are utilized at a rate higher than their regeneration is exemplary. In this case, the market price of sand and gravel is not a good indicator reflecting the scarcity of such natural resources as they do not incorporate the externalities released to the environment. In a like manner, in Italy and, e.g., in the Campania Region (southern Italy), limestone quarries have been exploited in the past without legislative limits, while also, currently, the situation is not much improved even in presence of a regional law due to the low penalties and lack of capacity of public administrations to enforce the restoration of damaged areas. The result is that, for example, the landscape of Caserta and of the neighbourhood municipalities (in which 15 quarries are located) is devastated [36].

Extraction companies are only profit-driven, and their cost curve does not incorporate the environmental costs of virgin material extraction. In the absence of a legislation or its presence with poor enforcement mechanisms (with limits to the use of natural resources and an appropriate value and rights to them), the extraction activities create environmental disasters. Soil is a very fragile ecosystem, and its generation required thousands of years. Not to mention that its role is essential for human well-being due to its multiple environmental functions [38,43]. Accordingly, an old quote that cites "the land cannot be treated by humans "as the miser treats his hoard of gold" Yourcenar, 1953 cited in La Repubblica Napoli [44] is very meaningful and appropriate.

Currently in Italy, compared to other countries such as the UK and Belgium, the price of natural aggregates is very low: 10 €/tonne versus 25 €/tonne in Belgium and 35 €/tonne in UK. The difference between the price of virgin inert materials and the price of recycled materials is higher than 15 € in Belgium and 12 €/tonne in the UK, while in Italy is only 3 €/tonne. Therefore, the constructor is not encouraged to use recycled materials instead of virgin materials. Moreover, landfilling costs are also higher in Belgium (100 €/tonne) and the UK (125 €/tonne) than in Italy (1–10 €/tonne) [45]. The high costs of landfilling are an important incentive to reduce the amount of C&DW going to landfills and favor selective demolition whenever possible. Again, also in this case, the use of LCA is highly recommended in order to assure that selective demolition is environmentally friendly compared to conventional demolition [46]. The economic costs, compared to conventional demolition process as well as the times for performing it [22], could increase as resulted in [28]. However, it is important to remark that both the costs and the socio-economic viability of selective demolition also depend on the specific local context [14] and the political framework that, as in the case of Italy, seems to progressively favor the adoption of deconstruction [47]. Although conventional demolition is a widespread practice currently worldwide [48], it does not encourage an improvement of quality of RA and its market development, still leaving NA as the main choice for the manufacturing of concrete. Selective demolition enables the separation and recovery of a higher quantity of materials, components, and products than conventional demolition which the goal is performing quickly and in the cheapest way the demolition activities. The recycling potential of the incoming materials is much lower as well as their quality [22,49]. Obviously, selective demolition better fits the European goals about the amount of C&DW to be recycled set by the Waste Framework Directive 2008/98/EC [50] and that of the Italian Government defined in the Legislative Decrees 50/2016 and 56/2017 [47]. Last but not least, selective demolition provides the opportunity to scale up other CE practices such as the reuse of construction products including concrete elements, with environmental, social, and economic benefits for companies (micro scale), construction industry (meso scale), and society (macro scale) [51].

Finally, the legislative decree (Legislative decree 'Milieuprestatieberekening van gebouwen' (art. 5.8 and 5.9), called MPG) introduced in the Netherlands in the year 2018 is an important best practice example to be underlined and shared with other countries [45] The decree requires the assessment of impacts by means of LCA for new residential and office buildings with a dimension higher than 100 m^2 [45].

5. Conclusions, Limitations, Policy Implications

The evaluation of the energy use and environmental impacts of the production of 1 m^3 of concrete by means of LCA is presented in this study. Five scenarios were modeled, defined, and compared for the purpose of identifying the best environmentally friendly concrete mixtures. Further, the impacts of coarse NA and coarse RCA production have been studied in order to understand their total ecological footprints and the main hotspots in each of the life cycles of these products.

From an energy and environmental point of view, it is certainly important to increase the use of coarse RCA for the production of concrete and replace coarse NA with coarse RCA. The results show that the characterized induced CED and environmental impacts improve when increasing percentages of coarse RCA are added to the mixture, up to a presence of only RCA treated in a mobile plant (CRCA 100). However, the impacts decline by only 10% for the CED and even less for GWP, while freshwater ecotoxicity (−63.4%), marine ecotoxicity (−76.8%), human carcinogenic toxicity (−27.1%), human non-carcinogenic toxicity (−77.9%), land use (11.6%), water consumption (−17.3%) improve to a much larger extent.

This study also assumed that the input of the coarse RCA consisted only of concrete. This hypothesis, indirectly, allowed reducing the gap in terms of quality of the coarse RCA obtained from a fixed or a mobile plant. In general, the fixed recycling plant is characterized by a greater number of processes from which it is possible to obtain a better quality of RCA. Therefore, to maintain the same quality of coarse RCA, it would be necessary to adopt a selective demolition process, in particular for the mobile plant, to assure that the materials entering as input to be recycled are well selected and less heterogeneous. In Italy, this demolition technique seems progressively encouraged by the legislation (Legislative Decrees 50/2016 and 56/2017) and suggested as relevant by the Italian association of cement and concrete producers for the purpose of enhancing the standard of excellence of recycled products and their markets. While the LCA literature shows that the relative ecological advantage of selective demolition is case-specific, some current pilot projects, e.g., in Finland, also highlight the important spillover positive effects that such techniques could have in advancing the CE transition towards other practices, such as reuse and in improving the well-being of construction companies, industries, society, and the natural environment.

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Abbreviations

Explanation of acronyms used in this study.

CE	Circular Economy
C&D	Construction and Demolition
LCA	Life Cycle Assessment
NA	Natural Aggregate
FA	Fine Aggregate
RA	Recycled Aggregate
RCA	Recycled Concrete Aggregate
CRCA	Coarse Recycled Concrete Aggregate
RAC	Recycled Aggregate Concrete
RC	Recycled Concrete
CC	Conventional Concrete
CED	Cumulative Energy Demand (composed of non-renewable fossil, non-renewable nuclear, non-renewable biomass, Renewable biomass, Renewable, wind, solar, geothermal, Renewable water)
Functional Unit	FU
Life Cycle Inventory	LCI
Life Cycle Impact Assessment	LCIA
GWP	Global Warming Potential

Appendix A

Table A1. UNEP recommendations useful to improve the environmental and social sustainability as well as circularity of sand management. Source: After UNEP [38].

UNEP Recommendations	Description
Recommendation 1	**Recognition of sand as a resource** that provides critical ecosystems services and is an essential material for the construction of vital infrastructures in towsn and cities worldwide.
Recommendation 2	**Place-based perspectives inclusion** for just sand transitions, ensuring the partecipation of all impacted people in decision-making, agenda-setting and action.
Recommendation 3	**Enable a paradigm shift to a regenerative and circular future.**
Recommendation 4	**Adopt strategic and integrated** policy and legal frameworks horizontally, vertically and Intersectional in agreement with local, national, and regional contexts
Recommendation 5	**Establish ownership and access to sand resources** through mineral rights and consenting
Recommendation 6	**Map, monitor and report sand resources** for transparent, science-based and data-driven decision-making
Recommendation 7	**Establish best practices and national standards**, and a coherent international framework
Recommendation 8	**Promote resource efficiency and circularity** by reducing the use of sand, replacing it with viable alternatives and recycling products made of sand when possible.
Recommendation 9	**Procurement of sand in an ethical, sustainable, and socially conscious way.**
Recommendation 10	**Restore ecosystems and compensate for remaining losses** by advancing knowledge, integrating the mitigation hierarchy, and promoting nature-based solutions

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