recycling

MDPI

Article

Environmental and Economic Comparison of Natural and Recycled Aggregates Using LCA

Adriana Dias [1], Salem Nezami [2], José Silvestre [2,*], Rawaz Kurda [3,4], Rui Silva [2], Isabel Martins [5] and Jorge de Brito [2]

1 c[5]Lab, Sustainable Construction Materials Association, 2795-242 Lisbon, Portugal; adias@c5lab.pt
2 CERIS, Civil Engineering Research and Innovation for Sustainability, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisbon, Portugal; salem.alnezami@tecnico.ulisboa.pt (S.N.); rui.v.silva@tecnico.ulisboa.pt (R.S.); jb@civil.ist.utl.pt (J.d.B.)
3 Department of Highway and Bridge Engineering, Technical Engineering College, Erbil Polytechnic University, Erbil 44001, Iraq; rawaz.kurda@tecnico.ulisboa.pt
4 Department of Civil Engineering, College of Engineering, Nawroz University, Duhok 42001, Iraq
5 LNEC, Laboratório Nacional de Engenharia Civil, 1700-066 Lisbon, Portugal; imartins@lnec.pt
* Correspondence: jose.silvestre@tecnico.ulisboa.pt

Abstract: Recycled aggregates (RAs) have been playing an important role in replacing natural aggregates (NAs) in concrete production, thereby contributing to a reduction in the extraction of natural resources and the promotion of a circular economy. However, it is important to assess the global impacts of this replacement, in both environmental and economic terms. In this study, an overview of the impacts of the production of natural and recycled aggregates is presented, using the life cycle assessment (LCA) methodology. Through this methodology, products with the same function are compared and information about the best solutions is given, considering their environmental and economic impacts. Studies with data collected from specific producers were compared, as well as environmental product declarations (EPDs) and generic databases, regarding the production of natural and recycled, coarse and fine, and rolled and crushed aggregates. This study intends therefore to provide the environmental and economic impact comparison at the global level through LCA from different data sources. According to this literature review, the best and worst environmental results are assigned to lower and higher transport distances, respectively. Regarding EPDs, the lowest environmental impacts are related to recycled coarse aggregates and the highest to natural coarse crushed aggregates. In terms of generic databases, the results are similar, with the lowest impacts associated with natural fine rolled aggregates and the highest to natural coarse crushed aggregates. In what concerns the economic impacts, in general, recycled aggregates are associated with the lowest costs. However, these results are highly dependent on transport distances and costs.

Keywords: construction and demolition waste; economic impacts; environmental impacts; life cycle assessment; natural aggregates; recycled aggregates

check for updates

Citation: Dias, A.; Nezami, S.; Silvestre, J.; Kurda, R.; Silva, R.; Martins, I.; de Brito, J. Environmental and Economic Comparison of Natural and Recycled Aggregates Using LCA. *Recycling* **2022**, *7*, 43. https://doi.org/10.3390/recycling7040043

Academic Editor: Domenico Asprone

Received: 9 May 2022
Accepted: 24 June 2022
Published: 30 June 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

One of the causes of increased toxic emissions is the production of NAs, which are also responsible for a significant consumption and depletion of natural resources. At the same time, the world generation of construction demolition waste (CDW) totals more than 10 billion tonnes per year [1]. This amount of CDW can be recycled and used as aggregates to overcome the issue of using NAs. For example, a study by Ginga et al. [2] shows that the European construction industry currently produces 924 million tonnes of CDW, which accounts for at least 30% of the total solid waste produced around the world. In addition, there is a high potential for using CDW as Ras in concrete production because most of its components have a high resource value. Several studies [3,4] have shown positive results for using RAs in structural concrete and road construction [5]. The advantages of using

RAs can be summarised as: (i) it reduces the production of NAs and preserves natural resources; (ii) it minimises the emission of CO_2 into the air and the costs of construction materials, especially for short-distance transportation scenarios; (iii) it preserves lands instead of landfilling them and decreases the need for new landfills, thus also leading to savings in costs; (iv) it offers more employment opportunities in the recycling industry [6].

Furthermore, landfilling continues to be the preferred solution for the management of CDW, but it causes significant environmental, economic, and social impacts because it contains materials that can contaminate soils and groundwater [7]. This, in turn, will indirectly affect public health. Thus, many studies have started searching for more sustainable solutions, namely by recycling CDW and reusing them in construction works, but this may also have environmental consequences because of increasing toxic emissions by the fuel consumed during transportation [8]. The critical issue here is how to identify the environmental advantages from recycling [9]. Life cycle assessment is the answer. It is an effective methodology, particularly because it contributes to measuring every elementary flow of the studied plant, comparing products and alternatives for the same use, and identifying the weakest points during the product life cycle. It is essential to assess any new material in terms of its performance, quality, economic, social, and environmental aspects simultaneously [10]. The LCA is an environmental control tool that can be applied to classify and determine the environmental aspects of the product and help find the environmental improvements during product development [11].

As mentioned above, the use of RAs can be an alternative to be used instead of NAs. Nevertheless, there are not many studies on this path, especially on the LCA of using RAs and NAs simultaneously [7]. Thus, the main goal of this paper is to compare the environmental and economic impact of RAs and NAs according to data from papers published in international journals. The source of RAs was only focused on concrete, and whether it contained fine or coarse RAs.

2. Methodology

As mentioned before, this study intends to show an overview of the production of natural and recycled aggregates for concrete based on environmental and economic LCA results. Thus, it was required to define: (i) the declared unit, which is the reference that allows the comparison of the products; (ii) the system boundaries, which define the limits of the study; and (iii) the impact categories, which allow the comparison of the results. The information related to the aggregates was collected from previous research studies, environmental product declarations, and generic databases.

The declared unit considered in this study was the production of 1 tonne of aggregates ready to be used in concrete production.

Based on the methodological flowchart (Figure 1), the global warming potential (GWP), non-renewable energy consumption (PE-NRe), and the cost of 1 tonne of natural and recycled aggregates from cradle to gate (A1–A3) were evaluated by considering the data given from: (i) generic databases such as Ecoinvent and European reference Life Cycle Database (ELCD); (ii) EPDs; and (iii) reference literature. The mentioned life cycle stages are explained in the following Section 2.1.

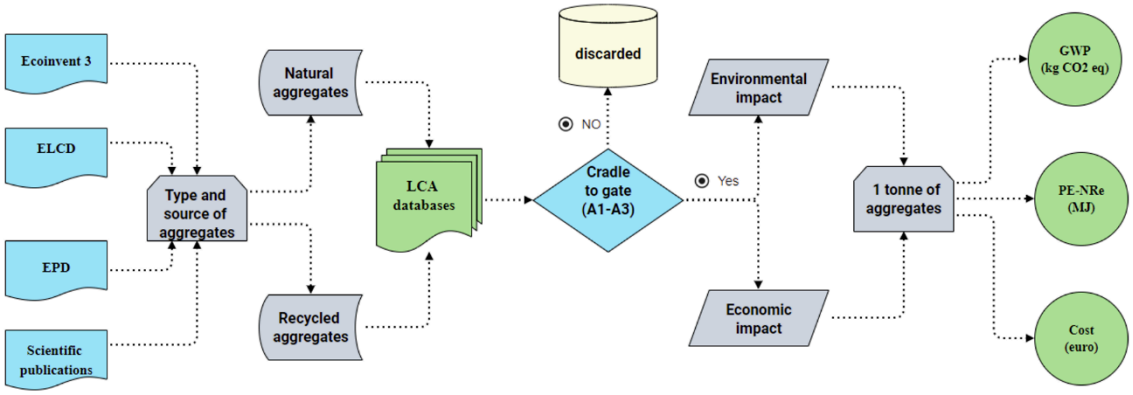


Figure 1. Flowchart of the data collection process.

2.1. System Boundaries

The system boundaries defined for most of the studies were from cradle to gate, related to product stages (A1–A3), which include raw material extraction and processing, transport of raw materials and manufacturing of the products. Some studies added option A4, from the construction process stage, related to the transportation impact of the construction product from the manufacturer to the building site. However, that was not considered because this study was focused only on A1–A3.

2.2. Type and Source of Aggregates

Extensive research was conducted to find LCA studies that addressed aggregates for concrete and that identified their type and source (Table 1). Based on the data collected from these studies, the aggregates can be coarse or fine, natural (rolled or crushed) or recycled (crushed). Additionally, NAs can be extracted from quarries or riverbeds. Furthermore, most of the aggregates that come from quarries are limestone, but some granitic and basaltic aggregates can also be found. From riverbeds, one can find sand and gravel. Regarding RAs, they are processed from CDW.

Table 1. Type and source of aggregate from each study.

Author		Type of Aggregate	Source of Aggregate
Tam (2008) [12]	NA	Produced from rocks	Quarry
	RA	Recycled concrete waste	Recycling plant
Marinković et al. (2010) [13]	NA	River aggregate	River
	RA	Recycled coarse aggregate	Demolished reinforced concrete structure
Jullien et al. (2012) [14]	NA	Site 1—amphibolites from Roselier Site 2 and 3—alluvial deposits, Fz and Fy (sand and gravel)	-
	RA	-	-
Simion et al. (2013) [15]	NA	Natural inert quarries	Quarry
	RA	C&D inert waste	CDW recycling plant
Tošić et al. (2015) [16]	NA	Fine and coarse river aggregate; fine and coarse crushed stone aggregate	-
	RA	Coarse recycled concrete aggregate	-
Faleschini et al. (2016) [17]	NA	High quality/low quality (gravel/sand)	Quarry
	RA	High quality/low quality	CDW recycling plant

Table 1. *Cont.*

Author		Type of Aggregate	Source of Aggregate
Hossain et al. (2016) [18]	NA	River sand/crushed stone	-
	RA	CDW/waste glass	-
Braga et al. (2017) [7]	NA	River/crushed (fine aggregate); Granitic/limestone (coarse aggregate)	River/quarry
	RA	Precast/demolished/cast in laboratory elements	Recycling plant
Fraj and Idir (2017) [19]	NA	Calcareous (Boulonnais landfill)	Boulonnais landfill
	RA	Low grade and high grade	Recycled concrete aggregate, demolished buildings
Rosado et al. (2017) [20]	NA	Basalt mineral	Basalt quarry
	RA	Mix CDW generation	CDW recycling plant facility
Estanqueiro et al. (2018) [21]	NA	Limestone	Quarry
	RA	CDW	Demolition site
Colangelo et al. (2018) [22]	NA	Natural sand and gravel Natural stone	-
	RA	CDW from concrete industry and marble sludge Cement kiln dust	-
Kurda et al. (2018) [23]	NA	Limestone; river sand	River/quarry
	RA	CDW	Recycling plant
Park et al. (2019) [24]	NA	Gravel (25 mm, 45 mm, 75 mm)	Sea, land and mountains
	RA	Waste concrete	Demolition and deconstruction of structures
Pradhan et al. (2019) [25]	NA	Basalt	Mine
	RA	CDW	Demolition site/recycling plant
Ohemeng and Ekolu (2020) [26]	NA	Fine NA	Quarry
	RA	Fine recycled concrete aggregate	Recycling plant
Kulekci et al. (2021) [27]	NA	-	-
	RA	Construction wastes	3 provinces in Turkey

2.3. Processing Characteristics

The processing characteristics depend on the origin of the aggregates. For example, NAs can be sourced from quarries or rivers. If the NAs are extracted from quarries, the process starts with stripping, then blasting, sorting, crushing, and washing (in some cases), and ends with stockpiling. For that purpose, several types of equipment are required, such as loaders, excavators, lorries, vibrating feeders, crushers, and conveyor belts. If the NAs come from rivers, the impact of the excavation, dredging, and collection must be considered as a first stage [18]. Regarding RAs, the recycled plant can be stationary or mobile. The first part of the process is the stockpiling, and then the CDW is sorted, crushed, and sieved.

2.4. Databases

Three types of databases were considered in this study: LCA datasets with site-specific data, EPDs, and generic databases, namely Ecoinvent and ELCD (Table 2). In the national context (Portugal), only two datasets were found in the literature review: one from Braga et al. [7], including data for coarse NAs and RAs, and fine NAs (rolled and crushed); the other one, from Estanqueiro et al. [21], with data regarding coarse natural and recycled crushed aggregates. Internationally, five reliable studies were considered from

four countries, France, Serbia, China, and Korea, with data from all types of aggregates. In addition, 13 EPDs from five different program operators (Figure 2) and seven generic LCA datasets from Ecoinvent and ELCD were also considered in this study (Table 3). Regarding the program operators, a major part of the selected EPDs are emitted by International EPDs from Sweden, as shown in Figure 2.

Table 2. Datasets for the production of coarse and fine, natural and recycled, rolled and crushed aggregates.

Aggregates	LCA Databases			
	Portugal Literature Review	International Literature Review	International EPD	Generic Databases
Coarse natural rolled	0	3	2	1
Coarse natural crushed	2	3	9	3
Coarse recycled crushed	2	5	4	0
Fine natural rolled	1	3	2	2
Fine natural crushed	1	2	2	0
Fine recycled crushed	0	1	0	0

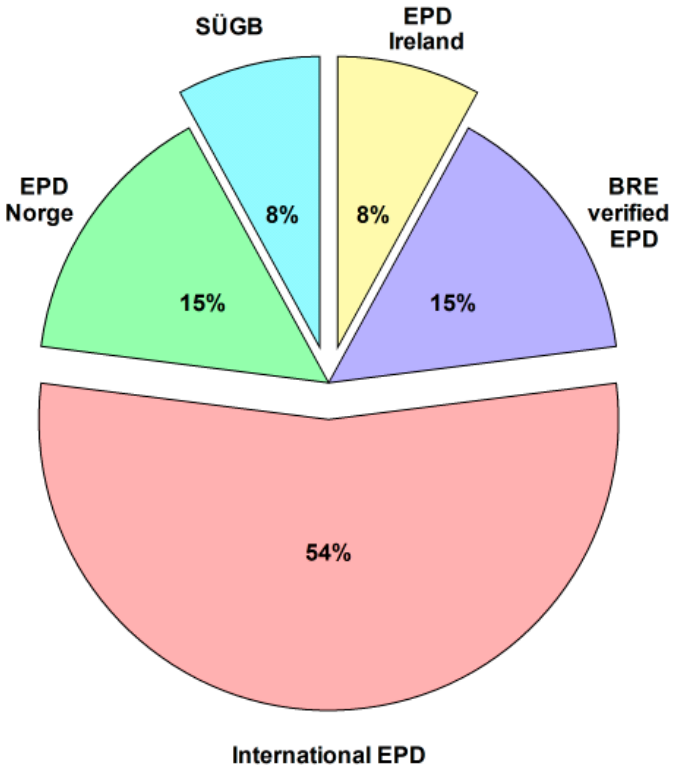


Figure 2. Program operators of the EPD.

Table 3. Generic databases.

System Process	Database
Basalt {RoW}| quarry operation | Cut-off, S	Ecoinvent 3
Gravel, crushed {RoW}| production | Cut-off, S	Ecoinvent 3
Gravel, round {RoW}| gravel and sand quarry operation | Cut-off, S	Ecoinvent 3
Limestone, crushed, for mill {RoW}| production | Cut-off, S	Ecoinvent 3
Sand {RoW}| gravel and quarry operation | Cut-off, S	Ecoinvent 3
Sand {RoW}| sand quarry operation, extraction from riverbed | Cut-off, S	Ecoinvent 3
Crushed stone 16/32 mm, open-pit mining, production mix, at the plant, undried RER S	ELCD
Gravel 2/32 mm, wet and dry quarry, production mix, at the plant, undried RER S	ELCD
Sand 0/2 mm, wet and dry quarry, production mix, at the plant, undried RER S	ELCD

2.5. Environmental Impacts and Methods

Several methods were used to assess the environmental impacts, including CML Baseline, Cumulative Energy Demand, Ecoindicator 99, Mat France, and Impact 2002+.

These impact assessment methods consider different environmental impact assessment categories, as presented in Table 4. However, the most important ones, related to carbon footprint and embodied energy, are GWP (or climate change) and energy use, the latter being expressed in primary energy, non-renewable (PE-NRe) or abiotic depletion, and fossil fuels (ADPF). Regarding the literature review, the most used method is CML Baseline, from the Netherlands, with four studies, then Cumulative Energy Demand, with two studies, and Eco-Indicator, Mat France, and IMPACT 2002+ with just one study each.

Table 4. Environmental impact assessment categories from each impact assessment method.

	CML Baseline	Cumulative Energy Demand	Eco-Indicator 99	Mat France	IMPACT 2002+
Number of studies	4	2	1	1	1
Abiotic depletion	X			X	
Abiotic depletion (fossil fuels)	X				
Acidification	X		X	X	
Air pollution				X	
Aquatic acidification					X
Aquatic ecotoxicity					X
Aquatic eutrophication					X
Carcinogens			X		X
Climate change			X		
Ecotoxicity			X		
Energy consumption				X	
Eutrophication	X		X	X	
Freshwater aquatic ecotoxicity	X				
Fossil fuels			X		
Global warming	X			X	X
Human toxicity	X				
Ionizing radiation					X
Land use			X		X
Marine aquatic ecotoxicity	X				
Minerals			X		X
Non-carcinogens					X
Non-renewable		X			X
Ozone layer depletion (ODP)	X		X	X	X
Photochemical oxidation	X			X	
Radiation					
Renewable		X			
Resp. inorganics			X		X
Resp. organics			X		X
Terrestrial acidification/nutrification					X
Terrestrial ecotoxicity	X				X
Water pollution				X	
Water usage				X	
Wastes				X	

3. Results and Discussion

In this section, the economic and environmental impacts from the sources identified are presented and discussed. Regarding the economic impacts, the distribution of NAs and RAs production costs is explained, as well as the final aggregate cost. In relation to

environmental impacts, the results are presented for the studies with site-specific data and then all the other results are compared through dispersion graphics.

3.1. Economic Impact of Natural and Recycled Aggregates

Economic assessment is usually carried out through a life cycle cost methodology, which considers all economic impacts of a product through its life cycle. However, none of the selected research studies had applied that approach. Instead, some conducted a cost–benefit analysis of producing aggregates for concrete [12,26] and others presented the cost of production of several types of aggregates for concrete [7,16].

The economic analysis includes the costs of the several stages of aggregate production, considering the costs of equipment, working capital, maintenance, labour, fuel, water, and fixed costs [12,26]. In the case study by Ohemeng and Ekolu [26], about 42% of NA production costs were shown to be related to environmental costs (e.g., landfill charges and air, and water emission costs) and transport costs, only 26% to processing costs (e.g., stripping, blasting, sorting, and crushing), and about 32% to the finished aggregates. Regarding RAs, only 21% of the costs were shown to be related to environment and transportation, 36% to processing, and the highest costs were related to finished aggregates (about 43%). Figure 3 presents the unit cost of each type of aggregate, collected from Portuguese companies [7], suppliers from Serbia [16], companies from Australia [12], and quarries and recycling plants in South Africa [26]. It can be concluded that, in most of the cases, the cost of RAs is lower, except in the case of Tošić et al. [16]. Additionally, the cost of the aggregates varies from region to region and, when also considering the transportation, the corresponding cost has a high impact on the overall cost of the aggregate.

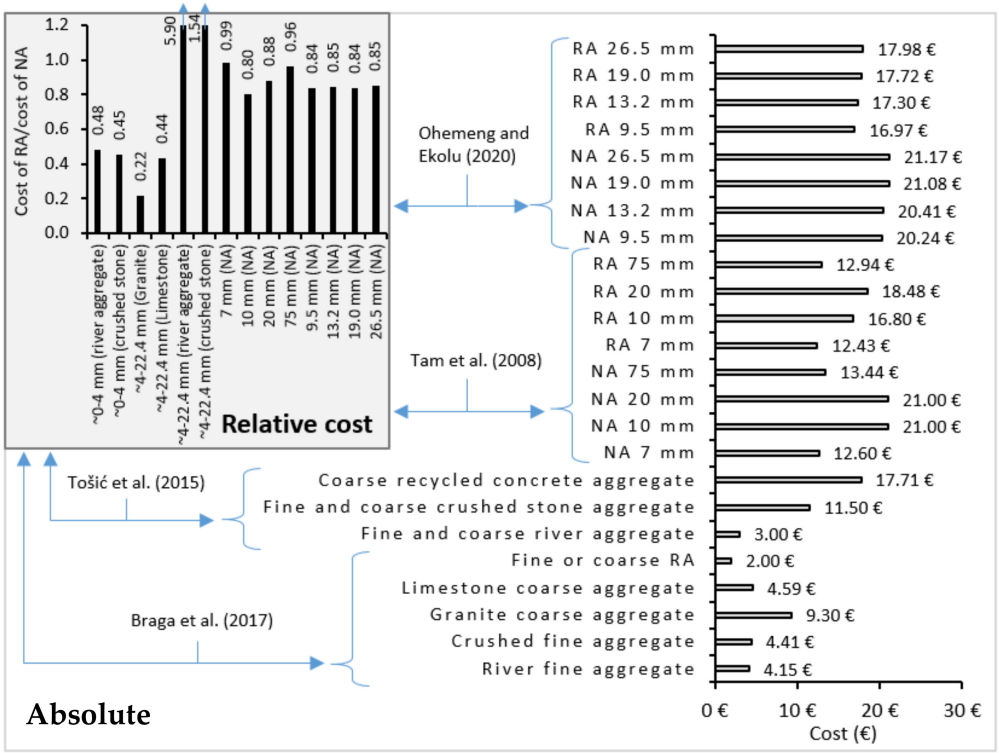


Figure 3. Absolute and relative costs of individual types of aggregates (cost of raw material production, per tonne).

3.2. Environmental Impact of Natural and Recycled Aggregates

For the environmental impact analysis of NAs and RAs, from the studies considered initially, only those with site-specific data from producers were selected. Table 5 presents the environmental impacts (in terms of GWP and PE-NRe) of the several types of aggregates grouped by coarse and fine, natural and recycled, and rolled and crushed.

Table 5. Type of aggregates used in concrete and corresponding environmental impacts, from the literature (GWP, in kg CO_2 eq; PE-NRe, in MJ).

Author	Coarse/ Fine	Natural/ Recycled	Crushed/ Rolled	Origin	GWP (kg CO_2 eq)	PE-NRe (MJ)
Braga et al. [7]	Coarse	Natural	Crushed	Granite	24.4	344
Braga et al. [7]	Coarse	Natural	Crushed	Limestone	31.4	441
Estanqueiro et al. [21]	Coarse	Natural	Crushed	Limestone	15.4	240
Fraj and Idir [19]	Coarse	Natural	Crushed	Limestone	4.39	320
Tošić et al. [16]	Coarse	Natural	Crushed	Limestone	2.12	21.9
Hossain et al. [18]	Coarse	Natural	Crushed	Limestone	32.0	496
Marinković et al. [13]	Coarse	Natural	Rolled	Undefined	1.39	14.8
Tošić et al. [16]	Coarse	Natural	Rolled	Undefined	1.34	11.2
Park et al. [24]	Coarse	Natural	Rolled	Undefined	14.3	-
Estanqueiro et al. [21]	Coarse	Recycled	Crushed	Concrete	24.4 a	444 a
Estanqueiro et al. [21]	Coarse	Recycled	Crushed	Concrete	20.5 b	381 b
Braga et al. [7]	Coarse	Recycled	Crushed	Concrete	7.44	108
Marinković et al. [13]	Coarse	Recycled	Crushed	Concrete	1.64	17.0
Fraj and Idir [19]	Coarse	Recycled	Crushed	Concrete	5.87	320
Hossain et al. [18]	Coarse	Recycled	Crushed	Concrete	11.0	211
Park et al. [24]	Coarse	Recycled	Crushed	Concrete	29.4 c	-
Park et al. [24]	Coarse	Recycled	Crushed	Concrete	38.1 d	-
Tošić et al. [16]	Coarse	Recycled	Crushed	Concrete	7.02 e	79.7 e
Tošić et al. [16]	Coarse	Recycled	Crushed	Concrete	5.19 f	60.8 f
Fraj and Idir [19]	Fine	Natural	Rolled	Limestone	4.39	320
Tošić et al. [16]	Fine	Natural	Rolled	Limestone	2.12	21.9
Braga et al. [7]	Fine	Natural	Rolled	Undefined	9.87	135
Hossain et al. [18]	Fine	Natural	Rolled	Undefined	23.0	341
Tošić et al. [16]	Fine	Natural	Rolled	Undefined	1.43	11.2
Braga et al. [7]	Fine	Natural	Crushed	Undefined	2.79	392
Hossain et al. [18]	Fine	Natural	Crushed	Undefined	33.0	518
Tošić et al. [16]	Fine	Natural	Crushed	Undefined	2.12	21.9
Hossain et al. [18]	Fine	Recycled	Crushed	Concrete	12.0	235

[a] Fixed plant, [b] Mobile plant, [c] Dry, [d] Wet, [e] 50% of recycled aggregate, [f] 100% of recycled aggregate.

The environmental impacts from each type of database (literature review, EPD, and generic databases) were compared through dispersion graphics, in order to validate the data and understand the relationship between GWP and energy use (Figure 4), for 1 tonne of each type of aggregates (FNR—fine natural rolled; FNC—fine natural crushed; FRC—fine recycled crushed; CNR—coarse natural rolled; CNC—coarse natural crushed; CRC—coarse recycled crushed). It can be observed that there are three points that are outliers, corresponding to crushed fine aggregates from Braga et al. [7] and both NAs and RAs from Fraj and Idir [19], probably due to the crushing method, in the first case, or to the particularities of each country. By analysing the remaining results, it can be observed that the best results in terms of environmental impacts are related to the coarse and fine natural rolled aggregates assessed by Marinković et al. [13] and Tošić et al. [16], produced in Serbia, probably due to the type of transport. The worst results are related to fine and coarse natural crushed aggregates, from Hossain et al. [18], produced in China, due to the transport distances.

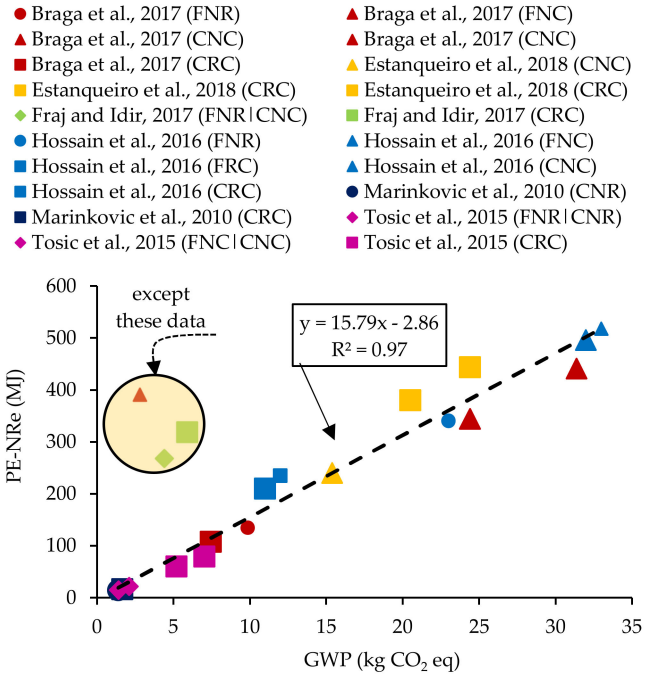


Figure 4. GWP (kg CO_2 eq) vs. PE-NRe (MJ) results from the literature review, per tonne of aggregate.

In terms of the data available in the selected EPDs [28–38], the relationship between GWP and ADPF was also confirmed (Figure 5). Two EPDs were excluded [39,40] because the results were not of the same order of magnitude of the remaining ones. Based on the two selected categories given by the report of the selected EPDs, the best results are related to coarse RAs and the worst to crushed coarse NAs.

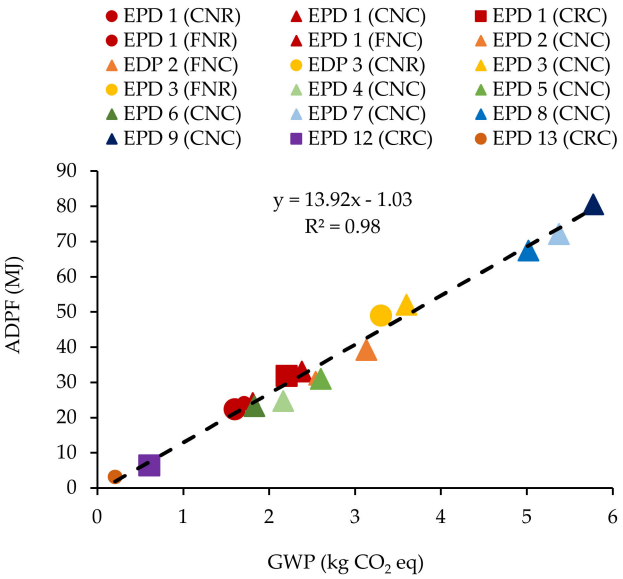


Figure 5. GWP (kg CO_2 eq) vs. ADPF (MJ) results from the EPD, per tonne of aggregate.

Regarding the generic databases from Ecoinvent and ELCD, the results are shown in Figure 6. The aggregate type with the lowest environmental impacts is sand of 0/2 mm produced at the quarry. The aggregate with the highest impact is crushed stone of 16/32 mm from open-pit mining. As expected, crushed aggregates have larger impacts than rolled aggregates due to the mechanisms and equipment needed for their production.

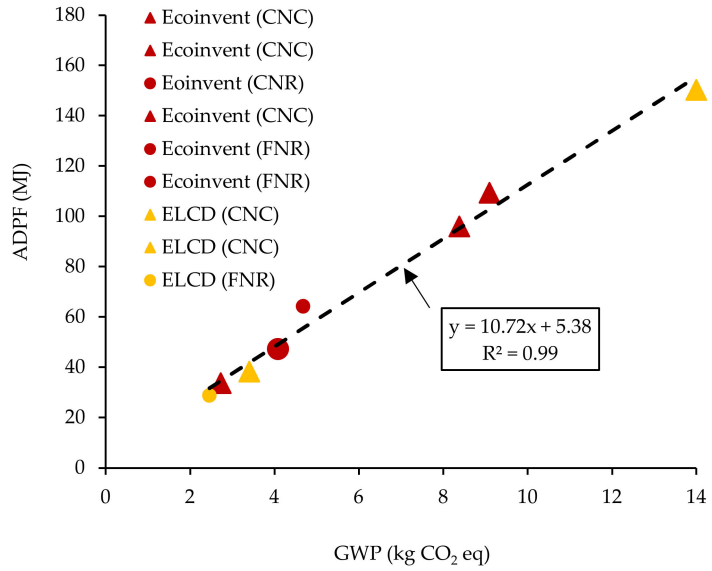


Figure 6. GWP (kg CO_2 eq) vs. ADPF (MJ) results from the generic databases, per tonne of aggregate.

Figure 7 presents the comparison of the LCA in terms of the GWP of coarse and fine aggregates, and Figure 8 presents the comparison in terms of their energy use. NAs are represented in blue and Ras are in green. The aggregates are divided by being rolled or crushed and by database type (literature review, EPD and generic databases). However, not all databases have results for all types of aggregates. For example, in generic databases, environmental impacts were neither found for RAs nor for fine natural crushed aggregates. In EPDs, values for fine recycled crushed aggregates were also not found. Regarding the other results, it is shown that the impacts from the literature review are generally higher than those of EPDs and generic databases. Once again, the highest impacts are related to coarse natural crushed aggregates and the lowest to coarse natural rolled aggregates, and the recycled aggregates have lower impacts than natural ones.

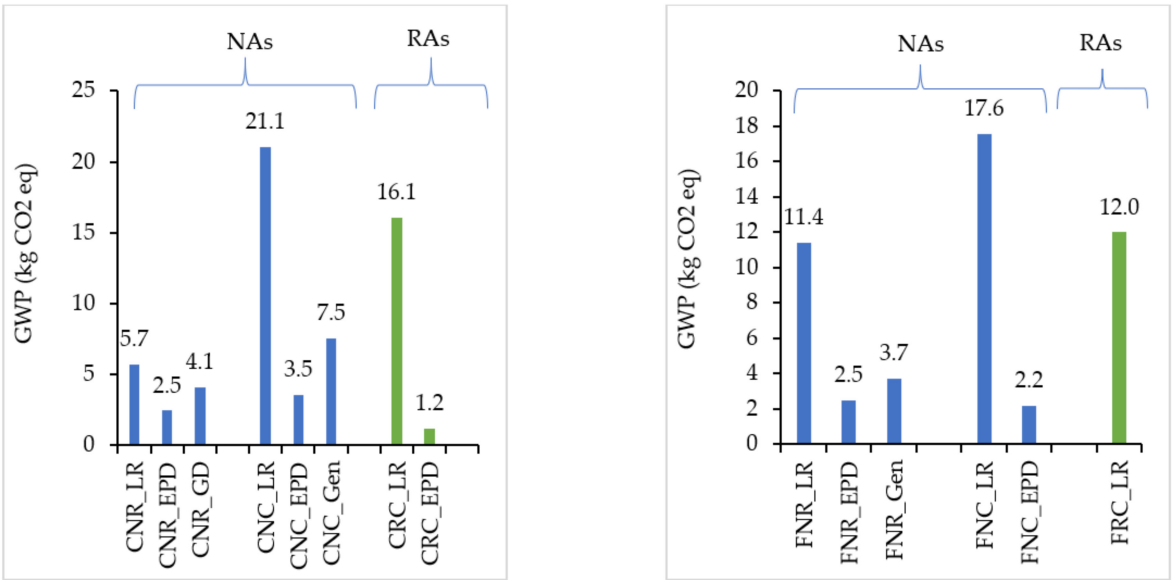


Figure 7. Comparison of the results in terms of GWP (kg CO_2 eq) of NAs and RAs coarse (**left**) and fine (**right**) aggregates from the different databases.

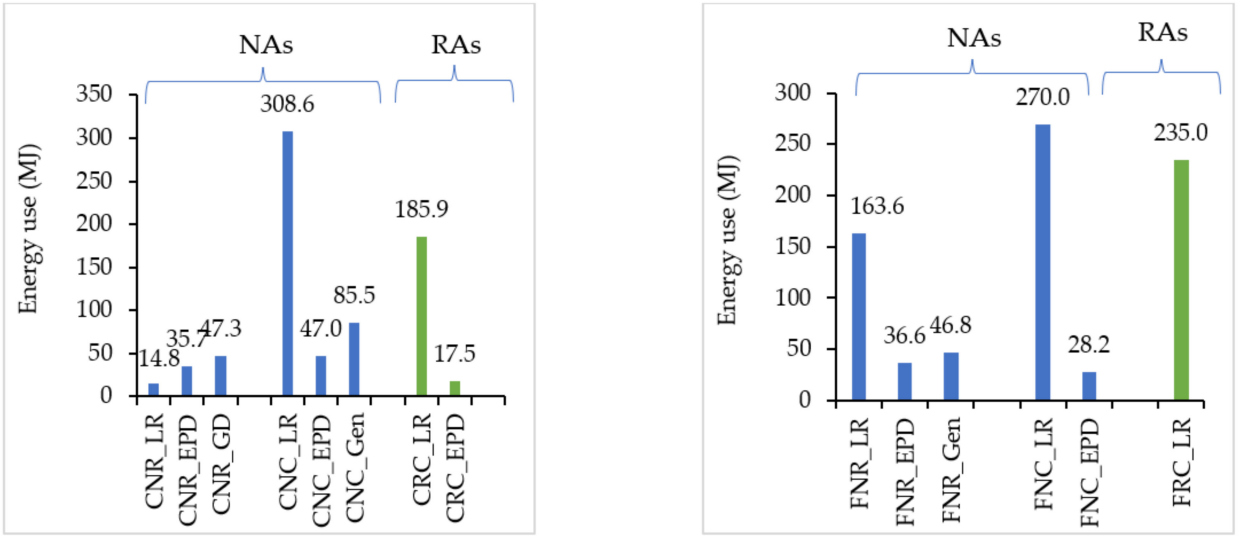


Figure 8. Comparison of the results in terms of energy use (MJ) of NAs and RAs coarse (**left**) and fine (**right**) aggregates from the different databases.

4. Conclusions

In this paper, the economic and environmental life cycle impacts of replacing RAs with NAs were highlighted. These results are important because the studies on the environmental and economic assessment of the production and replacement of these aggregates are still scarce despite the possibility of replacing RAs with NAs in concrete. The environmental and economic performance assessment of RAs is still underdeveloped. The comparison of the environmental performance was focused on GWP and PE-NRe. The analysis of the data of GWP (kg CO_2 eq) and energy use (MJ) for 1 tonne of aggregates showed that there is a linear relation for the three types of databases (literature review, environmental product declarations, and generic databases). Regarding economic assessment, none of the research studies considered a life cycle cost methodology, which considers all economic impacts of a product through its life cycle. In order to obtain reliable results, any economic analysis should include the costs of the several stages of aggregate production (costs of equipment, working capital, maintenance, labour, fuel, water, and fixed costs). Generally, these results are considered valid only for comparative purposes because they differ from one country to another and from one region to another. Still, transportation plays an important and influential role in the environmental and economic impact of both the RAs and NAs. Finally, to better understand the economic and environmental assessment of both RAs and NAs, and to reach more accurate results, further research is needed.

Author Contributions: Conceptualisation, A.D. and S.N.; methodology, J.S.; software, A.D. and R.K.; validation, J.S., R.K., R.S., I.M. and J.d.B.; formal analysis, A.D.; investigation, A.D. and S.N.; resources, J.d.B.; data curation, A.D. and S.N.; writing—original draft preparation, A.D. and S.N.; writing—review and editing, J.S., R.K., R.S., I.M. and J.d.B.; visualisation, A.D.; supervision, J.S., R.K., R.S., I.M. and J.d.B.; project administration, J.d.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors acknowledge the support of c^5Lab, CERIS, and LNEC.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wang, J.; Wu, H.; Tam, V.W.Y.; Zuo, J. Considering life-cycle environmental impacts and society's willingness for optimizing construction and demolition waste management fee: An empirical study of China. *J. Clean. Prod.* **2019**, *206*, 1004–1014. [CrossRef]
2. Ginga, C.P.; Ongpeng, J.M.C.; Daly, M.K.M. Circular economy on construction and demolition waste: A literature review on material recovery and production. *Materials* **2020**, *13*, 2970. [CrossRef] [PubMed]
3. Coelho, A.; de Brito, J. Environmental analysis of a construction and demolition waste recycling plant in Portugal-Part II: Environmental sensitivity analysis. *Waste Manag.* **2013**, *33*, 147–161. [CrossRef] [PubMed]
4. Silva, R.V. Use of Recycled Aggregate from Construction and Demolition Wastes in the Production of Structural Concrete. Ph.D. Thesis, Civil Engineering, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal, 2015.
5. Freire, A.C.; Neves, J.M.C.; Roque, A.J.; Martins, I.M.; Antunes, M.L. Feasibility study of milled and crushed reclaimed asphalt pavement for application in unbound granular layers. *Road Mater. Pavement Des.* **2021**, *22*, 1500–1520. [CrossRef]
6. Durgaprasad, K.; Koppala, S.; Guptha, M.R.V.S.G. Experimental investigation on fully recycled coarse aggregate concrete at various atmospheric conditions. *Int. J. Sci. Res. Rev.* **2018**, *7*, 1582–1591.
7. Braga, A.M.; Silvestre, J.D.; de Brito, J. Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates. *J. Clean. Prod.* **2017**, *162*, 529–543. [CrossRef]
8. Manfredi, S.; Pant, R. Supporting Environmentally Sound Decisions for Construction and Demolition (C&D) Waste Management. In *JRC Scientific and Technical Reports*; European Commission, Joint Research Centre, Institute for Environment and Sustainability: Luxembourg, 2011.
9. Silvestre, J.D.; de Brito, J.; Pinheiro, M.D. Environmental impacts and benefits of the end-of-life of building materials-calculation rules, results and contribution to a "cradle to cradle" life cycle. *J. Clean. Prod.* **2014**, *66*, 37–45. [CrossRef]
10. Tecco, N.; Baudino, C.; Girgenti, V.; Peano, C. Innovation strategies in a fruit growers association impacts assessment by using combined LCA and s-LCA methodologies. *Sci. Total Environ.* **2016**, *568*, 253–262. [CrossRef]
11. Pargana, N.; Pinheiro, M.D.; Silvestre, J.D.; de Brito, J. Comparative environmental life cycle assessment of thermal insulation materials of buildings. *Energy Build.* **2014**, *82*, 466–481. [CrossRef]
12. Tam, V.W.Y. Economic comparison of concrete recycling: A case study approach. *Resour. Conserv. Recycl.* **2008**, *52*, 821–828. [CrossRef]
13. Marinković, S.; Radonjanin, V.; Malešev, M.; Ignjatović, I. Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Manag.* **2010**, *30*, 2255–2264. [CrossRef]
14. Jullien, A.; Proust, C.; Martaud, T.; Rayssac, E.; Ropert, C. Variability in the environmental impacts of aggregate production. *Resour. Conserv. Recycl.* **2012**, *62*, 1–13. [CrossRef]
15. Simion, I.M.; Fortuna, M.E.; Bonoli, A.; Gavrilescu, M. Comparing environmental impacts of natural inert and recycled construction and demolition waste processing using LCA. *J. Environ. Eng. Landsc. Manag.* **2013**, *21*, 273–287. [CrossRef]
16. Tošic, N.; Marinković, S.; Dašić, T.; Stanić, M. Multicriteria optimization of natural and recycled aggregate concrete for structural use. *J. Clean. Prod.* **2015**, *87*, 766–776. [CrossRef]
17. Faleschini, F.; Zanini, M.A.; Pellegrino, C.; Pasinato, S. Sustainable management and supply of natural and recycled aggregates in a medium-size integrated plant. *Waste Manag.* **2016**, *46*, 146–155. [CrossRef]
18. Hossain, M.U.; Poon, C.S.; Lo, I.M.C.; Cheng, J.C.P. Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. *Resour. Conserv. Recycl.* **2016**, *109*, 67–77. [CrossRef]
19. Fraj, A.B.; Idir, R. Concrete based on recycled aggregates-Recycling and environmental analysis: A case study of Paris' region. *Constr. Build. Mater.* **2017**, *157*, 952–964. [CrossRef]
20. Rosado, L.P.; Vitale, P.; Penteado, C.S.G.; Arena, U. Life cycle assessment of natural and mixed recycled aggregate production in Brazil. *J. Clean. Prod.* **2017**, *151*, 634–642. [CrossRef]
21. Estanqueiro, B.; Silvestre, J.D.; de Brito, J.; Pinheiro, M.D. Environmental life cycle assessment of coarse natural and recycles aggregates for concrete. *Eur. J. Environ. Civ. Eng.* **2018**, *12*, 429–449. [CrossRef]
22. Colangelo, F.; Petrillo, A.; Cioffi, R.; Borrelli, C.; Forcina, A. Life cycle assessment of recycled concretes: A case study in southern Italy. *Sci. Total Environ.* **2018**, *615*, 1506–1571. [CrossRef]
23. Kurda, R.; Silvestre, J.D.; de Brito, J. Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash. *Resources, Conserv. Recycl.* **2018**, *139*, 407–417. [CrossRef]
24. Park, W.J.; Kim, T.; Roh, S.; Kim, R. Analysis of life cycle environmental impact of recycled aggregate. *Appl. Sci.* **2019**, *9*, 1021. [CrossRef]
25. Pradhan, S.; Tiwari, B.R.; Kumar, S.; Barai, S. Comparative LCA of recycled and natural aggregate concrete using Particle Packing Method and conventional method of design mix. *J. Clean. Prod.* **2019**, *228*, 679–691. [CrossRef]
26. Ohemeng, E.A.; Ekolu, S.O. Comparative analysis on costs and benefits of producing natural and recycled concrete aggregates: A South African case study. *Case Stud. Constr. Mater.* **2020**, *13*, e00450. [CrossRef]
27. Kulekci, G.; Yilmaz, A.O.; Cullu, M. Experimental investigation of usability of construction waste as aggregate. *J. Min. Environ.* **2021**, *12*, 63–76.
28. *FSKB-2018-1-ECOINVENT*; Average EPD for Aggregates. SÜGB: Bern, Switzerland, 2018.
29. *NEPD-1537-527-EN*; Crushed Stone Construction Aggregate products, Oslo and Bærum. The Norwegian EPD Foundation: Oslo, Norway, 2018.

30. *S-P-02081*; Environmental Product Declaration for Aggregates from Copenhagen, Terminal for Marine Aggregates–Avedøre. The International EPD System: Stockholm, Sweden, 2020.
31. *S-P-00843*; Environmental Product Declaration for Aggregates from the Stationary Crushing Plant RamNAslätt. The International EPD System: Stockholm, Sweden, 2017.
32. *S-P-01640*; Environmental Product Declaration for Aggregates from Uddevalla Quarry-Glimmingen. The International EPD System: Stockholm, Sweden, 2020.
33. *S-P-00528*; EPD Average Aggregate–Holcim Romania. The International EPD System: Stockholm, Sweden, 2014.
34. *NEPD-2750-1447-EN*; Crushed Stones and Aggregates, Produced at DC Seljestokken Aggregates AS. The Norwegian EPD Foundation: Oslo, Norway, 2021.
35. *BREG EN EPD No.: 000205*; Granite Aggregate-Glensanda. BRE Global: Watford, UK, 2018.
36. *BREG EN EPD No.: 000199*; Limestone Aggregate. BRE Global: Watford, UK, 2018.
37. *S-P-03101*; Recycled Aggregate Products. EPD International AB: Stockholm, Sweden, 2021.
38. *EPDIE 20-22*; Recycled Aggregates. Irish Green Building Council: Dublin, Ireland, 2020.
39. *S-P-00426*; Environmental Product Declaration (EPD) of Secondary Raw Materials or Aggregates of Industrial Origin-Sand Matrix. International EPD System: Lomello, Italy, 2013.
40. *S-P-00427*; Environmental Product Declaration (EPD) of Secondary Raw Materials or Aggregates of Industrial Origin-AGMatrix. International EPD System: Lomello, Italy, 2013.