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LIFE CYCLE ASSESSMENT OF THE PRODUCTION OF NATURAL AND RECYCLED AGGREGATES FOR CONCRETE: A CASE STUDY IN THE PROVINCE OF BRESCIA

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Abstract

The construction sector in Europe consumes about 50% of the total available raw materials, using enormous quantities of natural resources and soil from which these raw materials are extracted. At the same time, construction and demolition waste (CDW) accounts for about 35% of all waste produced both at the European and national levels, with approximately 60 million tonnes produced annually in Italy alone. The aim of this study, using the Life Cycle Assessment (LCA) methodology, was to analyse the environmental performance of the production process of recycled aggregates (RA) from CDW compared to natural aggregates (NA) for concrete production. In terms of overall environmental impact, the LCA highlighted that the production of recycled aggregates from construction and demolition waste has a significantly lower impact compared to the extraction of natural aggregates from quarries. The results of the LCA confirmed the importance and environmental advantages of using recycled aggregates in the construction sector, as they contribute to reducing the extraction of natural resources and the overall environmental impact of the production process. However, it is important to note that the actual assessment of environmental impact also depends on various specific factors of the case study, such as the technologies employed, transportation distances, and the management of CDW.

Key words: construction and demolition waste, life cycle assessment, natural aggregates, recycled aggregates

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1. Introduction

As is now well known, one of the global themes of the new millennium is undoubtedly the fight against climate change. In this sense, Europe has been implementing sustainable policies for some time now aimed at safeguarding our planet, which is rapidly heading towards irreversible climate change. These policies, in addition to being aimed at all production sectors, also aim to raise awareness among the population about a more conscious use of resources. The adoption of a circular economy plays a key role in this challenge, as it counters the linear model of production and consumption by aiming to maximize the reuse, recycling and restoration of existing resources. Through the circular economy, resource use can be optimized, reducing pressure on natural sources and helping to ensure access to valuable mineral resources for future generations (Agrawal, 2023).

According to Eurostat studies, in 2020, the total amount of waste produced in the 27 member states of the European Union from all economic activities amounted to 2.151 million tonnes, and in particular, the amount of waste produced by construction and demolition activities is the highest and represents about 37% of all waste produced (including municipal solid waste) (Eurostat, 2022). Italy, with a production of about 66 million tonnes of CDW, is the fourth European country in terms of construction and demolition waste production, after France, Germany, and the Netherlands. Regarding the recovery of these wastes, depending on the individual country, recovery

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rates range from 70 to 95%, according to Eurostat (Eurostat, 2022).

According to official data from ISPRA, Italy fully reflects the European situation; in fact, the recovery rate of CDW (excluding excavated soil and rocks) is over 78%, which is above the 70% target set by Directive 2008/98/EC for 2020 (ISPRA, 2022). At the same time, the construction industry, in addition to being the largest producer of waste contributes significantly to the environmental crisis as it is one of the sectors most responsible for land use, energy and resource consumption, with an incidence of around 30% on total energy consumption and 40% on material consumption (IEA, 2022).

To identify and measure the energy and materials utilized throughout the entire life cycle of a product, including the emissions that are released into the environment such as greenhouse gases, toxic substances, and waste, Life Cycle Assessment (LCA) methodology is gaining increasing prominence and importance. As seen, the use of recycled aggregates can widely replace natural aggregates, and the goal is to improve their quality to increase their possibilities of use (Piccinali et al., 2022). However, most studies focus on the utilization of RA as a substitute for NA and the impacts associated with their use in concrete production (Hossain et al, 2016; Jian et al., 2021; Turk et al., 2015) or on different methods of C&D waste management, without emphasizing their production process (Kucukvar et al., 2014, Liu et al. 2020).

For this reason, this work aims to analyze the entire life cycle of the production of RA and extraction of NA only, identifying and evaluating opportunities for environmental improvement, in the specific case of a treatment plant located in the province of Brescia. The evaluation also focused on the environmental impacts generated by the transport of C&D waste from the construction site to the plant, which is the most critical factor (Colangelo et al., 2018; Mah et al., 2018; O'Brien et al., 2009).

2. Material and methods

The study was conducted applying the LCA methodology according to the UNI EN ISO 14040:2021 and UNI EN ISO 14044:2021 (Ente italiano di normazione, 2021a, 2021b) standards respectively titled "Environmental management - Life cycle assessment - Principles and framework" and "Environmental management - Life cycle assessment - Requirements and guidelines", and implemented using the PCR (product category rules) in accordance with UNI EN ISO 15804:2021 "Sustainability of construction works - Environmental product declarations - Product category rules for construction products" (Ente italiano di normazione, 2021c).

2.1. LCA methodology

The criterion for evaluating the environmental impact of the production of both types of aggregates is based on the LCA methodology. The two UNI EN ISO standards that regulate the application of LCA provide for four different iterative phases, including 1) Goal and scope definition, 2) life cycle inventory (LCI) analysis, 3) life cycle impact assessment (LCIA) calculation and 4) results interpretation (Fig. 1).

The first phase of LCA study sets the goals and scope, including the functional unit (FU), system boundary, and data requirements for the life cycle inventory (LCI). Selecting these parameters is crucial, as the FU provides a basis for comparing results. The second one, the LCI phase involves collecting necessary data for the elementary flow from processes involved in the product linked to the FU, while the third phase, the LCIA converts this information to environmental impact scores. The LCIA methodology must be determined before LCI data collection, in line with the defined study goal and scope. The final phase is results interpretation, which includes identifying significant issues, evaluating completeness, sensitivity, and consistency, drawing conclusions, stating limitations, and making recommendations. Impact categories refer to the categories expressed by the 15804:2021 methodology.

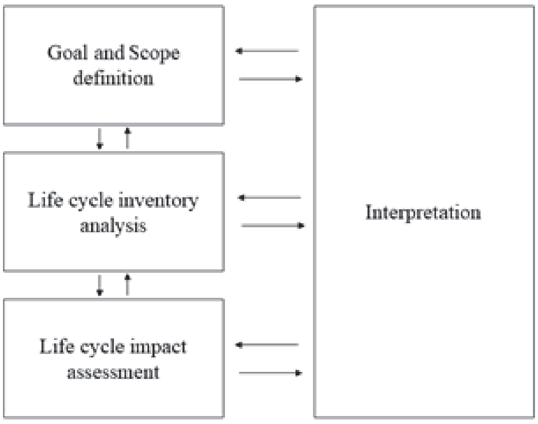

Fig. 1. Phases of an LCA (adapted from UNI EN ISO 14040:2021)

2.1.1. Goal and scope definition and functional unit

This work aims to identify the environmental impacts during the life cycle related to the production of natural aggregate and recycled aggregate from construction and demolition waste for concrete production. Both types of aggregates, recycled and natural, were analyzed so that once produced, they had the same function and were both certified according to the UNI EN 12620:2019 standard "Aggregates for concrete" so that they could be compared with each other.

The functional unit used for the study is 1 ton of aggregate produced and ready to be used in a concrete production plant.

2.1.2. System boundaries and case study

The system boundaries for both analyses conducted are defined as "from cradle to gate", according to what is expressed in UNI EN ISO 15804:2021. These boundaries encompass the A1-A3 product phases, which include the extraction of raw materials (only applicable in the case of natural aggregates), transportation of raw materials, and product manufacturing. While some studies include option A4, which considers the transportation impact of construction products from the manufacturer to the construction site during the construction process stage, it was not taken into account in this study as the focus was solely on A1-A3.

The case study, from which primary data for analysis was collected, is a treatment plant located in the province of Brescia. This site is particularly unique because a quarry for extracting virgin material is also present in the same area.

As regards the RA production, once demolished mainly from small demolitions, the CDW is transported to the plant. Upon arrival at the plant, after verifying the necessary documentation and checking for non-hazardousness, the CDW is unloaded in a designated area and sorted according to its EWC code. Before being crushed, the waste undergoes a preliminary process of removing iron and reducing its volume through the use of a mechanical clamp. Finally, there is a manual removal phase for other materials such as plastics or wood present in the CDW, which are collected separately. In this case, no specific mechanical removal processes such as flotation or air injection are required. However, the quantity of such materials is very low as there is already a preliminary manual removal phase at the construction site. Once the preliminary processes are completed, the material is moved from the deposit area to the crusher's mouth by a wheel loader. The mobile crusher is a machine that allows the granulometric reduction of CDW through a crushing process, while at the same time separating the metallic materials still present within the waste. The crushed CDW, not yet RA, is stored in designated lots awaiting a leaching test to confirm the cessation of its waste qualification.

As regards the NA, the extraction is carried out using a dredger that excavates inside a water basin. This dredger operates on electric current. Once extracted, the natural aggregate is transported via conveyor belts to a sieve that is responsible for separating it into different sizes (gravel and sand of different dimensions). During this process, there is no need to wash the aggregates as they are extracted directly from a water basin. As a result, there are several piles of different sizes at the output of the sieve, which are then moved to storage yards using dumpers. Fig. 2 graphically represents the system boundaries under analysis. Regarding the production of recycled aggregates, the environmental impact analysis process begins immediately after demolition, when construction and demolition waste is transported to the plant.

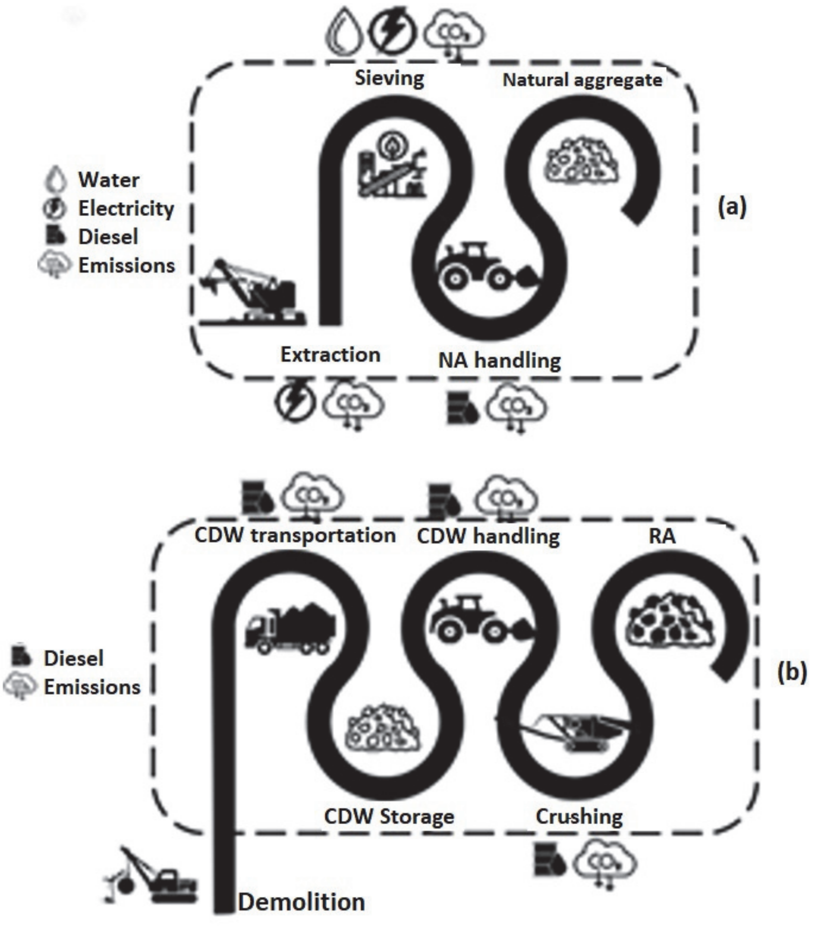

Fig. 2. (a) System boundary of the natural aggregate extraction process (b) System boundary of the recycled aggregate production process

2.2. Data collection and inventory analysis

The inventory of the production phase of both types of aggregate is based on primary data collected directly from the production plant of these two aggregates. When data collection was not possible due to a lack of information, the Ecoinvent v3.6 database (allocation, cut-off by classification) was used.

Technical visits and site inspections were carried out at the plant under analysis to collect the inventory data necessary to quantify the flows of materials, energy, and environmental emissions associated with the production process. Specifically, to better represent the studied reality in this LCA analysis, all processes related to the extraction and processing phases of natural inert materials and the treatment of C&D waste for RA production were adequately reconstructed based on the collected operational data. Regarding the process of extraction and processing of NA, the electrically powered extraction dredge and the fixed processing plant, also powered by electricity, were considered. On the other hand, for the process of C&D waste treatment, the mobile plant (MOBY 1001 jaw crusher) powered by diesel fuel was considered. Quantifications of the total amount of material treated per day are listed in Table 2, to facilitate then the possible reconstruction of environmental impacts obtained in data processing.

After evaluating the daily quantities processed by the treatment plants, information was collected on the energy consumption of the single stages, as well as The consumption of internal transport in the treatment plant. Especially, Information collected was about the consumption of electricity (extraction dredge and fixed plant), diesel fuel (mobile plant and handling equipment), and water (washing natural aggregates and for dust suppression that may arise during the handling and discharge of materials from conveyor belts). Information about the specific consumptions are listed in Table 3. It should be noted that, since the C&D waste treatment process is a dry process, no water consumption is expected during its operation.

Furthermore, after evaluating the consumption and quantities processed, the required processing times have also been taken into consideration. Taken directly at the plant, they refer to the time required to crush one ton of C&D waste, the extraction of one ton of AN, and the time required to transport the processed materials from one point of the plant to another. As for the loader, the times also refer to the time required to load the mobile crushing plant. These are listed in Table 4.

The data for which it was necessary to use the Ecoinvent database mainly refer to energy sources whose origin could not be reconstructed in order to better calculate the environmental impact of the processes in the boundaries of the study.

2.3. Life cycle impact assessment

The impact categories chosen in accordance with the UNI 15804:2021 standard and all the impact categories provided by this standard have been used and analyzed. SimaPro 9.1 was used to build the LCIA model and impact analysis. The following impact categories have been evaluated: *climate change; ozone depletion; ionizing radiation; photochemical ozone formation; particulate matter; human toxicity, non-cancer; human toxicity, cancer; acidification; eutrophication, freshwater; eutrophication, marine; eutrophication, terrestrial; ecotoxicity, freshwater; land use; water use; resource use, fossils; resource use, minerals, and metals.* For all the impact categories, individual emission factors were identified so that the amounts of emissions associated with specific categories per unit of output could be calculated. Then, total emissions were calculated by multiplying the activity data by the relevant emission factors.

After that, to represent and compare the individual impact categories with each other, it was necessary to apply the different normalization factors related to each of them. The characterization factors are listed in Table 5.

Table 2. Quantity of excavated NA and processed CDW daily

Treatment	***NA***	***RA***
	t/day	***t/day***
Natural aggregates extraction dredge	2500	---
Natural aggregates fixed processing plant	2000	---
Mobile plant for CDW treatment	---	155

Table 3. Processes energy and water consumption

Treatment Machinery	***Diesel***	***Electric Energy***	***Water***
	L/t	***(kWh/t)***	***L/t***
Natural aggregates extraction dredge	---	1.6	---
Natural aggregates fixed processing plant	---	1.75	1.25
Mobile plant for CDW treatment	0.14	---	---
Loader	0.07	---	---

Table 4. Processes duration

Treatment machinery	***Time (min)***
Natural aggregates extraction dredge	0.27
Natural aggregates fixed processing plant	0.27
Mobile plant for CDW treatment	0.4
Loader	0.4

Table 5. Normalization factor for each impact category

Impact category	***Normalization factor***
Climate change	0.0001235
Ozone depletion	18.64
Ionizing radiation	0.000237
Photochemical ozone formation	0.02463
Particulate matter	1680
Human toxicity, non-cancer	4354
Human toxicity, cancer	59173
Acidification	0.018
Eutrophication, freshwater	0.6223
Eutrophication, marine	0.05116
Eutrophication, terrestrial	0.005658
Ecotoxicity, freshwater	0.00002343
Land use	0.00000122
Water use	0.00008719
Resource use, fossils	0.00001538
Resource use, minerals and metals.	15.71

2.4. Life cycle interpretation

For both studies conducted (RA, NA), the environmental impacts of each main compartment are assessed in the Climate change category to determine which is the hot spot of the treatment solution, in order to define the best solution to reduce the environmental impact generated by the production of recycled aggregate.

3. Results and discussion

Before assessing the individual impact categories as explicitly required by UNI EN 15804:2021, an assessment of the overall impacts in terms of CO_2eq was carried out. This assessment is very important because it shows the Global Warming Potential (GWP) of individual products to be compared. Subsequent diversification into impact categories is seen as necessary to specify the individual environmental effects of individual production steps. Figure 3 represents the total environmental impacts related to the production of AN and RA. As regards the total environmental impacts, 2.47 $kgCO_2$eq for AN and 4.7 $kgCO_2$eq for AR are released into the atmosphere during the production process. In this case, regarding the transport of the recycled aggregate from the production site to the treatment plant alone produces 3.43 $kgCO_2$eq accounting for about 70% of the total. The outcome demonstrates that RA production has a higher harm compared to NA extraction.

After the first assessment conducted on the total impacts, analyses have been also developed on all other impact categories as depicted in Fig. 4. Regarding the results obtained from this analysis, with the exception of Eutrophication freshwater, Land use and Water use, all other categories have impacts for natural aggregate ranging from 80% to 30% less for natural aggregate in comparison with recycled aggregate.

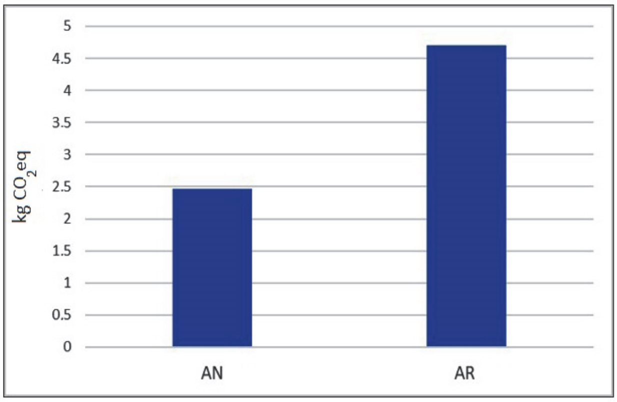

Fig. 3. Global warming potential related to NA and RA

Specifically, the impact categories that obtained a higher difference are *photochemical ozone formation*, *particulate matter*, and *eutrophication marine*, for all three the difference is about 80 percent between the two types of aggregate, directly referring to the use of diesel.

In fact, the combustion of fossil fuels, such as the diesel used by trucks, generates high amounts of NOx, which contributes to the eutrophication and acidification of the environment (Ferronato et al., 2022) and increases air pollution due to the increase in particulate matter (Borghi et al., 2018).

In contrast, for the impact category referring to climate change, expressed in kgCO_2 eq, the difference in environmental impact is about 50 percent. On the other hand, the impact categories of eutrophication freshwater, land use, and water use, which have less impact for RA compared to NA, are due to the direct extraction of material from the water and the greater consumption of soil caused by the area affected by the extraction plant (Luo et al., 2022). As for the water use category, the high difference is due to the processing plant of natural aggregates (NA) that uses water for washing the aggregates, unlike the recycled aggregates (RA) that use a dry production system (Renzulli et al., 2016). According to Marinković et al. (2010), the outcome shows that the production of natural aggregates has a lower impact compared to recycled aggregates. However, due to the different operations involved in the production of RA, a hotspot analysis is needed to investigate the main impact contributors.

3.1. Recycled aggregates production hotspot analysis

The impact of RA production on the environment is illustrated in Fig. 5 for all impact categories. In this case, the transportation of C&D waste from the construction site to the treatment plant represents the largest environmental burden in all categories of the RA production process as confirmed by Blengini and Garbarino (2010). In fact, in most non-toxic categories, the transportation of CDW is a major contributor to the overall impact results (Butera et al., 2015).

In this specific case, for average transportation distances of 20 km, the impact due to the transportation of materials varies from 65% to 97% for different impact categories. Despite all processes for the production of recycled aggregates running on diesel, the average transportation distance remains the primary source of environmental impact in all analyzed impact categories.

Specifically, it ranges from a maximum value of 97% for mineral resource utilization and land use, to a minimum value of 65% for the Human toxicity cancer category. As for the other 14 categories, impacts due to transport are about 70-75% of the total. This result has been consistently found in various literature studies focusing on this topic. In fact, the feasibility of a waste scenario is highly dependent on transportation distance and diesel use (Mah et al., 2018; Papadaki et al., 2022).

Therefore, based on the results obtained from natural aggregate extraction, it was decided to develop additional scenarios that would reduce transportation distances. It has been decided, in fact, to reduce the transportation distance of the CDW to 0 km, as it is the same distance traveled by the NA since it is produced and processed in the same facility. As demonstrated in Fig. 6, eliminating transportation distances leads to a significant decrease in environmental impacts.

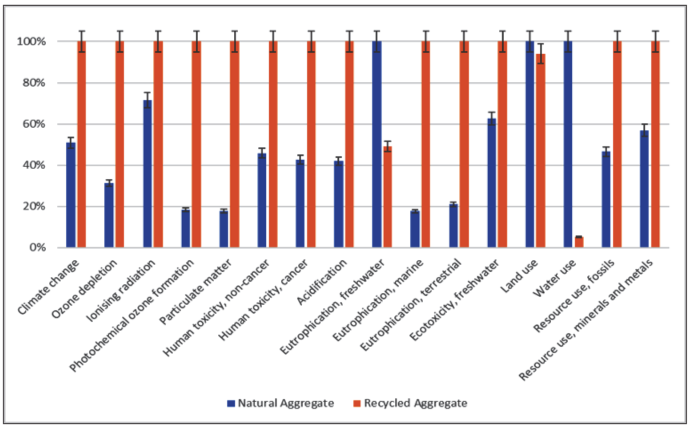

Fig. 4. Environmental impacts for RA and NA for each impact category

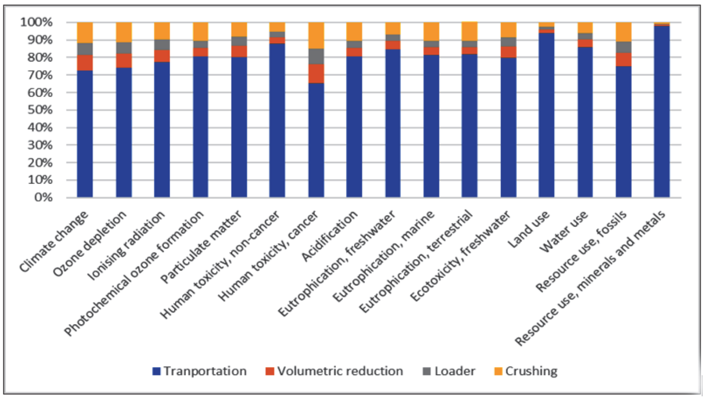

Fig. 5. RA production percentage contribution relative to each impact category

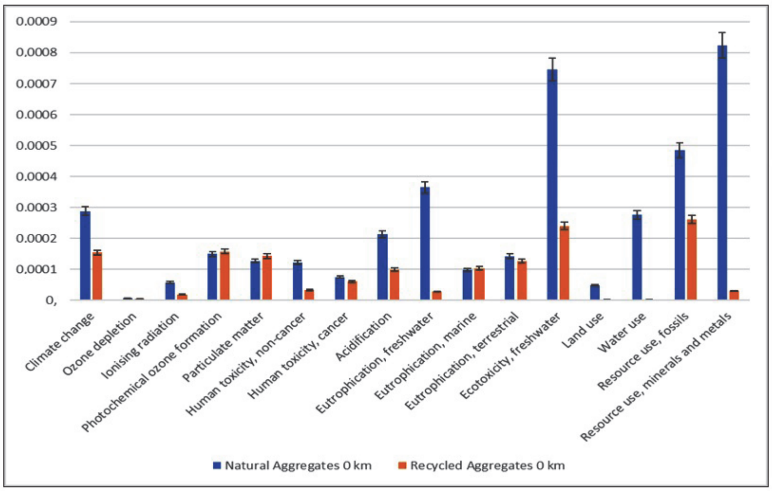

Fig. 6. Normalized impacts calculated for each impact category (No distance considered)

For all impact categories except photochemical ozone formation, particulate matter, and eutrophication in marine environments, the elimination of the transportation distances in the case of the production of recycled aggregates, still have an impact higher than the one for NA extraction, while all other categories show a considerable reduction with decreasing transportation distances (Butera et al., 2015). The result for these impact categories is due not only to the impact of transportation but also to the numerous processing operations carried out on-site, reducing the transportation of CDW alone would not lead to excessive savings (Borghi et al., 2018; Butera et al., 2015).

Specifically, when it comes to the freshwater ecotoxicity category, it shows one of the biggest disparities between the two types of aggregates, second only to the resource use of minerals and metals. This is primarily because of the water usage for washing NA, and, by the modeling of the Italian energy mix production, which, at the Italian level incorporates 14% hydroelectric energy (Borghi et al. 2018). The analysis of the subsystems in the recycling chain has confirmed the essential role of transportation and emphasizes the need for a better understanding and efficient management of the collection and distribution network. If there are excessive distances or the use of inefficient collection systems, it can compromise the overall environmental performance. (Blengini and Garbarino, 2010)

Considering zero transport distances, a reduction of environmental impacts by over 70% is achieved compared to the case study. However, this scenario was proposed to enable a pure comparison between the aggregate production stages. This is useful since our case study represents an exceptional case where CDW is delivered to the plant to produce RA, while AN is extracted directly from the quarry. The comparison between aggregate production processes is extensively studied in the literature.

Numerous studies, including Hossain et al. (2016) and Simion et al. (2013), have confirmed the lower environmental impact of AR production compared to AN without considering transportation distances from the production sites to the treatment plants.

4. Conclusions

In conclusion, this paper conducted a comprehensive Life Cycle Assessment (LCA) analysis to compare the environmental performance of recycled aggregates (RA) derived from construction and demolition waste (CDW) with natural aggregates (NA). Considering the case study, the LCA analysis determined that when accounting for waste transportation to the treatment facility, the production of RA has a significantly higher environmental impact compared to the extraction of NA. This finding highlights the importance of evaluating transportation and the need for careful material delivery planning to reduce environmental impacts.

However, when transportation is not considered and only the production processes is evaluated, a substantial reduction in environmental impacts for the production of RA compared to NA has been demonstrated.

Nevertheless, it is crucial to consider site-specific factors, such as waste management practices, transportation distances, and the energy mix used by the treatment plant when assessing the environmental impact of aggregate production. Local circumstances and infrastructure play a significant role in determining the overall environmental performance of each option.

Further research and case studies are encouraged to investigate specific contexts, advancements in recycling technologies, and waste management practices. This will enable improvements in environmental performance and promote the widespread adoption of recycled aggregates in construction projects.

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References

Agrawal R., Bhagia S., Satlewal A., Ragauskas A.J., (2023), Urban mining from biomass, brine, sewage sludge, phosphogypsum and e-waste for reducing the environmental pollution: Current status of availability, potential, and technologies with a focus on LCA and TEA, *Environmental Research*, **224,** 0013-9351.

Blengini G.A., Garbarino E., (2010), Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix, *Journal of Cleaner Production*, **18**, 1021-1030.

Borghi G., Pantini S., Rigamonti L., (2018), Life cycle assessment of non-hazardous Construction and Demolition Waste (CDW) management in Lombardy Region (Italy), *Journal of Cleaner Production*, **184**, 815-825.

Butera S., Christensen T.H., Astrup T.F., (2015), Life cycle assessment of construction and demolition waste management, *Waste Management*, **44**, 196-205.

Colangelo F., Petrillo A., Cioffi R., Borrelli C., Forcina A., (2018), Life cycle assessment of recycled concretes: A case study in southern Italy, *Science of the Total Environment*, **615**, 1506-1517.

Ente italiano di normazione, (2021a), UNI EN ISO 14044:2021 - Environmental management - Life cycle assessment - Requirements and guidelines, (in Italian).

Ente italiano di normazione, (2021b), UNI EN ISO 14040:2021 - Environmental Management - Life cycle assessment - Principles and framework, (in Italian).

Ente italiano di normazione, (2021c), UNI EN 15804:2021 - Sustainability of buildings - Environmental product declarations - Development framework rules by product category, (in Italian).

Eurostat, (2022), Eurostat – Statistics, On line at: https://ec.europa.eu/eurostat/databrowser/view/env_wasgen/default/table?lang=en

Ferronato N., Guisbert Lizarazu G.E., Gorritty Portillo M.A., Moresco L., Conti F., Torretta V., (2022), Environmental assessment of construction and demolition waste recycling in Bolivia: Focus on transportation distances and selective collection rates *Waste Management and Research*, **40**, 793-805.

Hossain M.U., Poon C.S., Lo I.M.C., Cheng J.C.P., (2016), Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA, *Resource Conservation and Recycling*, **109**, 67-77.

IEA, (2022), Building Analysis, On line at: https://www.iea.org/reports/buildings

IISP, (2022), Special waste report 2022, (in Italian), On line at: https://www.isprambiente.gov.it/it/pubblicazioni/rapporti/rapporto-rifiuti-speciali-edizione-2022

Jian S.M., Wu B., Hu N., (2021), Environmental impacts of three waste concrete recycling strategies for prefabricated components through comparative life cycle assessment, *Journal of Cleaner Production*, **328**, 129463, https://doi.org/10.1016/j.jclepro.2021.129463.

Kucukvar M, Egilmez G, Tatari O., (2014), Evaluating environmental impacts of alternative construction waste management approaches using supply-chain-linked life-cycle analysis, *Waste Management & Research*, **32**, 500-508.

Liu J, Huang Z, Wang X., (2020), Economic and Environmental Assessment of Carbon Emissions from Demolition Waste Based on LCA and LCC, *Sustainability*, **12**, 6683, https://doi.org/10.3390/su12166683.

Luo W., Liu S., Hu Y., Hu D., Kow K.W., Pang C., Li B., (2022), Sustainable reuse of excavated soil and recycled concrete aggregate in manufacturing concrete blocks, *Construction and Building Materials*, **342**, 127917, https://doi.org/10.1016/j.conbuildmat.2022.127917.

Mah C.M., Fujiwara T., Ho C.S., (2018), Life cycle assessment and life cycle costing toward eco-efficiency concrete waste management in Malaysia, *Journal of Cleaner Production*, **172**, 3415-3427.

Marinković S., Radonjanin V., Malešev M., Ignjatović I., (2010), Comparative environmental assessment of natural and recycled aggregate concrete, *Waste Management*, **30**, 2255-2264.

O'Brien K.R., Ménaché J., O'Moore L.M., (2009), Impact of fly ash content and fly ash transportation distance on embodied greenhouse gas emissions and water consumption in concrete, *International Journal of Life Cycle Assessment*, **14**, 621-629.

Papadaki D., Nikolaou D.A., Assimakopoulos M.N., (2022), Circular environmental impact of recycled building materials and residential renewable energy, *Sustainability*, **14**, 4039, https://doi.org/10.3390/su14074039.

Piccinali A., Diotti A., Plizzari G., Sorlini S., (2022), Impact of recycled aggregate on the mechanical and environmental properties of concrete: A review, *Materials*, **15,** 1818, https://doi.org/10.3390/ma15051818.

Renzulli P.A., Notarnicola B., Tassielli G., Arcese G., Di Capua R., (2016), Life Cycle Assessment of steel produced in an italian integrated steel mill, *Sustainability*, **8**, 719, https://doi.org/10.3390/su8080719.

Simion I.M., Fortuna M.E., Bonoli A., Gavrilescu M., (2013), Comparing environmental impacts of natural inert and recycled construction and demolition waste processing using LCA, *Journal of Environmental Engineering and Landscape Management*, **21**, 273-287.

Turk J., Cotič Z., Mladenovič A., Šajna A., (2015), Environmental evaluation of green concretes versus conventional concrete by means of LCA, *Waste Management*, **45**, 194-205.