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Life Cycle Assessment of Concrete Recycling Solutions in Light of Their Technical Complexity

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Abstract: Waste management is a key step for addressing both the environmental impact and the growing demand for resources in the construction industry. To answer these challenges, various technologies are available, carrying different environmental impacts and sociotechnical implications. For concrete waste, recycling is the most common solution. Two main recycling roads were identified, leading to products that have low or high value and implying different technical developments and environmental impacts. This study first proposed to characterize recycling technologies by their technical degree, reflecting the complexity needed to process waste. It secondly compared their environmental impacts using LCA methodology to assess which technical complexity led to minor environmental consequences and under what conditions. The results revealed that the technologies with a low technical degree tended to have a lower environmental impact than the ones with a higher technical degree when only the generated impacts were considered. The reverse was observed when considering the aggregated impacts due to the environmental benefits provided by the potentially avoided products.

Keywords: waste management; sociotechnical approach; life cycle assessment; construction waste; recycling

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1. Introduction

Construction and demolition waste (CDW) represents around 30% of the total waste stream globally and 36% of the total waste stream in Europe [1,2]. This share is expected to grow due to ongoing urbanization [3]. CDW management has to tackle the various environmental impacts generated by both the transportation and treatment of the residual materials. In the meantime, the growing number of construction projects leads to a high demand for materials and resources [2], anticipating growing impacts on the biosphere. Among CDW, concrete is particularly challenging, as it is the most used component and the largest waste stream in the construction sector [4].

Given this context, laws and regulations have been put in place in several parts of the world to give orientations as to the favorable treatment options. In Europe, CDW management is embedded in a circular economy framework [3,5], as this concept aims at reconciling production activities and respect for the environment [6]. More specifically, managing waste from a circular economy perspective could lead to waste minimization and resource use maximization [7] by promoting the recovery of waste so that it becomes a secondary resource. Circular strategies such as reuse, refurbishing, recycling, or energy recovery can indeed help address both the issue of environmental impacts and resource availability by avoiding the use of primary raw materials [8].

However, for a given strategy, a hierarchy may exist among several treatment options, depending on their technical complexity and the output's added value. For example, Gharfalkar et al. (2015) [9] defined three types of recycling based on the economic value of the secondary products: downcycling produces lower-value products compared with the substituted material, recycling produces products with similar value, and upcycling produces higher value products. These different types of recycling may consider different types of technology that can allow such variability.

In the case of concrete recycling, the sector is moving from end-of-pipe solutions (landfilling) to recycling and even reemployment in some contexts, but this last alternative involves new thinking on all the design and conception of a building and is thus not frequently done [1]. Regarding recycling, a two-category classification has been proposed. The first category is downcycling, which refers to the production of downgraded aggregates used in applications such as backfilling [1,3]. This application gives little value to concrete waste. However, it uses well-known and robust technologies (crushing). It can handle a large amount of waste at minimal cost, with no special need to identify a proper market. The second category is recycling, in which concrete waste is crushed into aggregates that can be used as input in recycled structural or non-structural concrete [1,3]. This recycling category uses crushing technologies as well but requires additional steps, knowledge, and precision to obtain recycled aggregates with a technical specification adapted to the end use. In return, the output product has greater value on the market. Furthermore, the sector is developing advanced recycling technologies that allow for the production of higher-quality aggregates [4], increasing their value compared with traditional technologies.

Along with the recycling products, the recycling technologies also have various environmental impacts and benefits. The life cycle assessment (LCA) is one of the main methodologies used to compare different waste management options in terms of environmental impacts [10]. The results from the LCA studies showed that, overall, recycling strategies present environmental benefits when compared to landfilling [10]. For concrete waste, studies show that traditional recycling technologies allow environmental benefits only when the potential avoided products are considered. Otherwise, the impacts of the recycling process itself can have a greater impact than the raw material production [1].

The advanced concrete recycling technologies allow the production of secondary sand and cement in addition to high-quality aggregates [11], providing greater potential environmental benefits. Indeed, even if they require extra energy and materials [11], they also allow greater avoided impacts due to the prevention of virgin aggregates, sand, and cement production. It results in a more beneficial balance than traditional recycling for most of the impact categories [11]. Their advantages also rely on the fact that the finest fractions of the product can be recovered, whereas it is eliminated in the traditional recycling roads [11]. It is also to be noted that those technologies are not yet available at the industrial scale [4], requiring further investments to become market-ready [12].

Given the above, concrete recycling is facing a technical trade-off between easy-to-implement technologies at a large scale but with low-added value products and not mature technologies but with promises of higher environmental and economic benefits. Furthermore, there is a lack that has been identified in the literature in studies considering both the technical aspects (technical complexity, ease of use, etc.) and the associated environmental impacts of waste treatment alternatives [13]. Indeed, comparing technologies based on the recycling classification (downcycling/upcycling) tends to favor those that provide high-value products. However, it overlooks the questions related to the dependency on waste providers/product buyers or technical simplicity that could be of importance for effective technical adoption [13].

To date, there is no methodology allowing us to characterize the various end-of-life solutions for concrete that look at the technology types involved in the recycling processes. Based on this gap, this study offered to analyze the environmental impacts of concrete waste management with a focus on the technical choice implications. It specifically proposed (i) highlighting the technical complexity of the concrete recycling technologies mobilized to process the waste by assessing their technical degree and (ii) identifying under which conditions each technology presents potential environmental benefits. To do so, this study proposed a characterization grid that allowed for the positioning of the technologies against each other and an assessment of their environmental impacts based on this positioning.

2. Methodological Proposal

The methodology was built in two distinct parts: the first one dealt with the development of an analytical grid that aims at positioning the technologies on a technical scale, and the second aimed at modeling the concrete waste recycling technologies to run an LCA. The general steps of the methodology are presented in Figure 1.

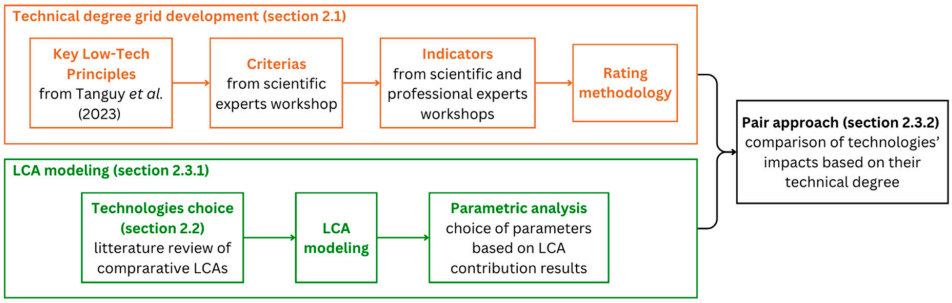


Figure 1. General methodology steps [14].

2.1. Technical Degree Evaluation

In this paper, the technical degree of a given recycling technology represents its technical complexity and ease of use compared with other technologies, assessed on various aspects: the amount of physical resources it consumes, the number of technical steps necessary to obtain the final recovery product(s), its dependency to external supply for waste, and its flexibility to varying inputs. The evaluation of these aspects takes the form of an evaluation grid composed of principles (the previously mentioned technical aspects), criteria (the different dimensions of the principles), and indicators (to make the criteria commensurable).

2.1.1. Choice of Principles, Criteria, and Indicators

This step of the methodology was inspired by a previous paper (Tanguy et al., 2023 [14]). This work has been taken as a basis for the development of the technical degree evaluation grid. The criteria and indicators selection was led by continuous collaborative work within the project team, in which scientific expertise was mobilized to select relevant aspects in the specific case of concrete waste management. The criteria choice relied on the relevance for the sector and the possibility of assessing the criteria easily, i.e., accessing the information to rate the indicator. The criteria and indicators choice were also confronted by three experts in the construction sector who gave their input on the relevance and key factors that should be taken into account in the grid used for rating concrete recycling technologies. These experts (the R&D development manager of a large construction company in France, a member of a professional association of construction companies in France, and a member of the national scientific institute on buildings, which carries out expertise and research activities on projects related to the construction sector),

were chosen based on their knowledge of the sector (including concrete recycling) and because of previous collaborations on past projects with the authors, in which sociotechnical aspects of construction activities were investigated.

The criteria and indicators for the four selected principles were then chosen as follows:

- Decreased resources consumption: The criteria were the material and energy consumption, and the indicators were the quantity of key materials and energy sources for the construction waste management technologies (steel, water, electricity, and diesel);
- Appropriation: Although it seemed more social than technical, the Appropriation principle included the technical simplicity criterion, which was relevant for the technical degree assessment. This criterion was assessed using two indicators: the number of steps in the recycling process and the type of equipment (fixed or mobile);
- Limited external dependency: The criterion chosen here was the upstream dependency, which was assessed with the supplier concentration and the average transportation distance covered by the waste. Since the actor responsible for the waste differs from the one operating the recycling process, we assumed that the more those indicators were high, the more the technology functioning was dependent on external supply;
- Back to basics: This principle, initially referring to the idea of going back to essential objects and decreasing the demand for new needs satisfiers, was more adequate for technical objects than for (waste management) systems. Thus, the flexibility criterion was defined to reflect the idea of a technology that is adequate for the need for waste management. The indicator was the ability to adapt when facing input flow variability, both in type and quantity.

The full technical degree evaluation grid for the concrete waste recycling technologies is presented in Table 1.

Table 1. Principles, criteria, and indicators selected to assess the technical degree of concrete waste recycling technologies.

Principle (from [14])	Criteria	Indicator
1. Decreased resources consumption	Material consumption	Steel quantity Water quantity
	Energy consumption	Electricity quantity Diesel quantity
2. Appropriation	Technical simplicity	Number of steps Type of equipment
3. Limited external dependency	Upstream dependency	Supplier concentration * Input average distance
4. Back to basics	Flexibility	Ability to adapt when facing input flow variability (type and quantity)

* Measured with the Herfindahl–Hirschman Index (HHI) [15,16]. For more details, see Table A1 (Appendix A), note 4.

2.1.2. Rating and Scores

To be able to rate the quantitative and qualitative indicators in a consistent way (as the ratings will be compiled in a single score), they were both rated on a scale ranging from 0 to 2, where 0 corresponds to a "low technical" degree and 2 to a "high technical" one (integers only, so three levels: 0, 1, or 2). For Principles 1 and 2, the rating choice was based on the literature review conducted on the environmental impact of concrete recycling (see Table A1 in Appendix A for more information on the distinction between the 0, 1, and 2 ratings). For Principle 3, the rating should be based on context-dependent

literature and/or expert opinions since it relies on geographical data that may be specific to one country or region. Moreover, no evidence was found suggesting that the "Input average distance", for example, may differ depending on (or even be correlated to) the chosen recycling technology. Therefore, in this study, since all technologies with the same geographical context were considered, the same rating was applied for the two indicators of Principle 3 (see Table A2). Finally, regarding Principle 4, qualitative description of the technologies found in [4] and in grey literature on deconstruction waste recycling did not allow the discrimination of the four technologies for the selected indicator ("Ability to adapt when facing input flow variability"). Therefore, to avoid larger uncertainties, the same rating was also applied to all studied recycling technologies.

The final criteria score was the average of the indicators' ratings, as we chose to apply an equal weighting for each indicator. Similarly, the score for each principle score was the average of its criteria scores, and the final score was the average of the principle scores.

2.2. Concrete Recycling Technologies Selection

The technologies selection was based on an LCA literature review focused on the comparison of recycling alternatives for concrete waste. The term "technology" refers in this work to the steps that enabled processing the waste to obtain the secondary materials. The waste recycling technologies were classified in two categories based on the secondary products they provide: low- or high-value aggregate [1,12]. The technologies selected for this study are presented in Table 2.

The traditional recycling technologies are the most common [11]: dry recycling (C1) consists of crushing and sieving the concrete waste to produce aggregates. It can be a mobile or fixed technology, the first being an advantage in terms of transportation and energy consumption [1]. Wet recycling (C2) is similar to dry recycling, with an extra step consisting of washing the aggregates to manage dust. This technology cannot be mobile [3]. These traditional technologies supply aggregates that are mainly used in backfilling, which is considered a low-value usage [1].

Advanced recycling technologies are being developed at the industrial scale [4] and are often cited as promising avenues to answer the environmental and regulatory challenges for the construction sector [4,11,17,18]. They are also based on crushing concrete waste, but specific processes have been developed to obtain aggregates with higher value, i.e., alternatives for virgin material in concrete production. The Advanced Dry Recovery process (ADR, C3) is based on crushing, sieving, and air knives to separate the concrete waste smallest fractions [4]. The Heating Air classification System (HAS, C4) is a complement to ADR and comes after the ADR process to deal with the finest fractions that come from the ADR process, in which the aggregates are separated thanks to heated air that carries ultrafine aggregates [4]. These technologies present advantages, as they allow for higher environmental benefits, which are pursued in recycling, but these processes are more energy-intensive compared with the traditional ones. They can also be mobile [3].

Table 2. Studied concrete recycling technologies.

Category	Technology	Description	Reference
Low-value aggregate	C1—Dry recycling	Main steps: crushing and sieving Products: coarse aggregates (backfilling, structural or non-structural concrete)	[1,19,20]
	C2—Wet recycling	Main steps: crushing, washing and sieving Products: coarse aggregates (backfilling, structural or non-structural concrete)	[1,20]

Table 2. *Cont.*

Category	Technology	Description	Reference
High-value aggregate	C3—Advanced Dry Recovery (ADR)	Main steps: crushing, ADR unit (rotor and air sifter) Products: coarse aggregates (structural concrete)	[3,4,11,12]
	C4—Heating Air classification System (HAS)	Main steps: crushing, ADR unit, HAS unit (burner, cyclone sluice, compressor) Products: coarse aggregates, sand and cement (structural concrete)	[3,4,11,12]

2.3. Environmental Impact Comparison Approach

This section introduces the methodology related to the environmental assessment and the comparison approach followed to situate the waste recycling technologies with regard to each other. The environmental impacts of the concrete recycling technologies were assessed following the LCA methodology.

2.3.1. System Modeling

This section presents the system boundaries, the inventory, and the modeling hypothesis followed, considering that the functional unit was the treatment of 1 ton of concrete waste. The LCA was run using SimaPro v9.4, with the ecoinvent v3.8 Unit database [21] and the ReCiPe 2016 (H) impact assessment methodology.

As the system of interest here is the waste recycling technology in itself, the system excluded the upstream life cycle stages and began when the waste was ready to be processed. It ended when the secondary product was in its final form, excluding the use by another actor. To represent the waste recycling technologies as accurately as possible, the processes were modeled based on two main flow categories: machinery and operation [22]. Nevertheless, due to data availability, some processes were modeled only with the operation flows, which is the common way of modeling these processes in most references [11,23,24].

The system boundaries, processes, and flows used to model the technologies are displayed in Figure 2. The default geographical choice for the processes was France or Europe. When dealing with flows for which the origin was unknown, the choice was based on the literature. The detailed inventory for each technology and the processes used are available in Tables S1 and S2 (Supplementary Materials), respectively. The data came from LCA studies on concrete recycling [1,11,18–20,22–26], grey literature on building waste management [27,28], and ecoinvent database [21]. The LCA study considered the avoided products, which corresponded to the products that can be substituted by the ones produced by recycling, i.e., virgin gravel, sand, and/or cement. The processes used for the modeling of avoided products are available in Table S2.

2.3.2. Comparison Approach

The general principle of the comparison approach was to consider each possible technology "couple" (a combination of two technologies) and evaluate their positioning for the studied environmental impact categories. We chose this pair approach to ease the results' analysis and reveal the variability among them. A couple was composed of a technology with a low technical degree compared with a technology with a higher one. This way, we were able to determine if the technology with the lowest technical degree had lower/higher impacts compared with the one with a higher technical degree.

To achieve this, we first used a parametrized analysis to create a sample of technology modeling, aiming to base the results not only on the base case model (i.e., using the data presented in Tables S1 and S2) but also on a broader range of cases. This sample was

constructed by varying the values of selected parameters, which are presented in Table 3. The choice of the parameters to be varied was based on the LCA results for the base case: the parameters directly related to the technologies functioning and responsible for the largest part of the impacts were selected. The parameter variation was applied to the flow that was involved in the process carrying the largest impacts.

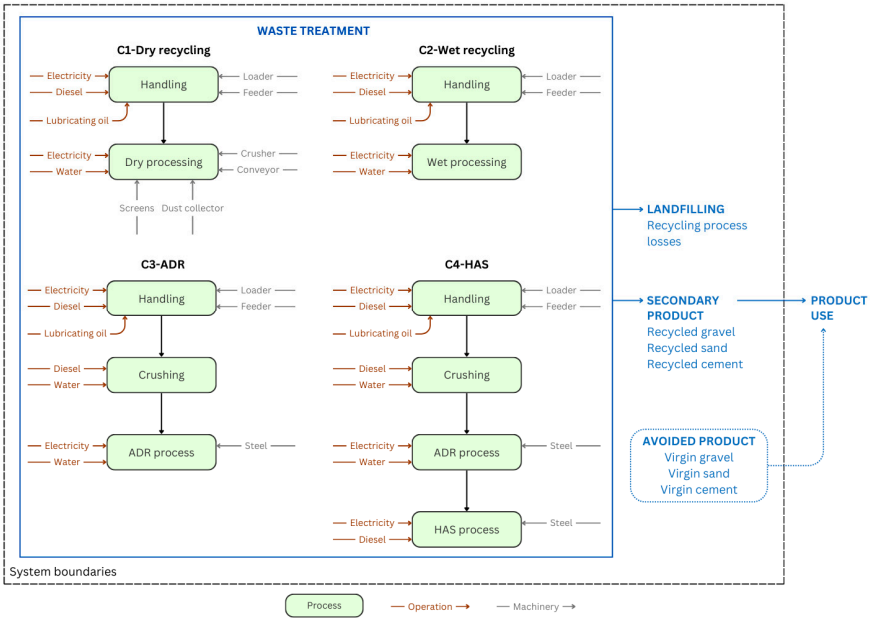


Figure 2. System boundaries, processes, and flows for the LCA of concrete waste recycling technologies.

Then, to perform the technologies' comparison, a randomized procedure was followed to explore various possibilities while limiting the bias in the considered combinations. This approach was inspired by the sensitivity analysis developed by Coelho and De Brito (2013) [29] for the LCA of a construction waste recycling site. The procedure is presented in Figure 3. From the possible values for each parameter, a list was established (step A in Figure 3). Then, a parameters set was formed (step B) and attributed to a technology (step C). Finally, all the possible couples were defined (step D), and one set attributed to the first technology was confronted with another set attributed to the second technology forming the couple (step E). This set confrontation was called a "pair". For each technology couple, 20 pairs were studied, forming the sample from which the conclusions were drawn. The parameter values of each set and the pairs studied are available in Tables S3 and S4, respectively.

Table 3. Selected parameters and their variation considered for the LCA parametrized analysis.

Parameter	Value Variation
Inventory parameters	
Electricity consumption	Low value (−20%) Base value High value (+20%)
Diesel consumption	Low value (−20%) Base value High value (+20%)
Processes parameters	
Electricity source	Base mix (France) China mix USA mix

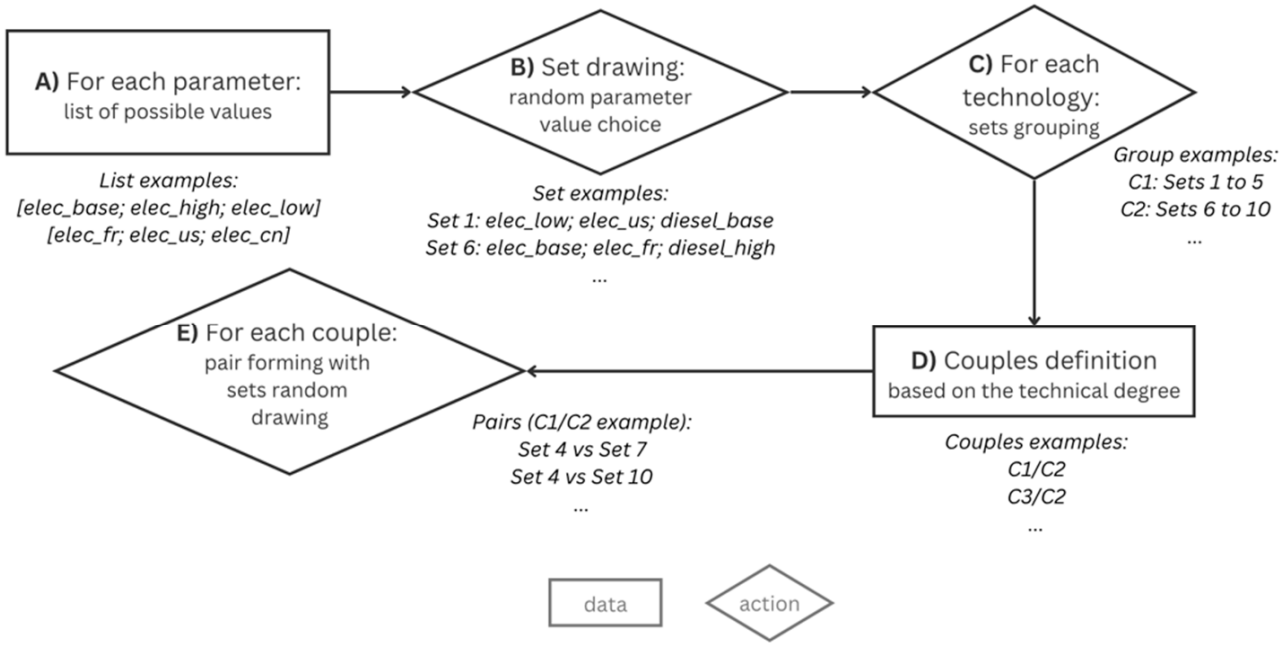


Figure 3. Randomized procedure for the comparison of technologies.

Finally, the proportion of pairs in which the technology with the lowest technical degree had a greater or lesser impact than the one with the highest technical degree was calculated. The impact difference was classified into five categories to take into account the uncertainty due to the LCA modeling and calculation:

- Much lower impact: The impact of the technology with the lowest technical degree was >50% lower than the one with the highest;
- Lower impact: The impact difference was situated between 20 and 50% lower;
- Similar impact: The impact difference was within a ±20% range;
- Higher impact: The impact difference was situated between 20 and 50% higher;
- Much higher impact: The impact of the technology with the lowest technical degree was >50% higher than the one with the highest technical degree.

3. Results

This section presents the technical degree of the studied concrete recycling technologies and the LCA results regarding the comparison of the technologies' environmental impact in regard of their technical degree.

3.1. Technical Degree

The technical degree of the studied technologies is presented in Figure 4. The results are to be interpreted in a relative way and not an absolute one due to the rating methodology. C1 had the lowest technical degree, and C2 and C4 had the highest. In this study, the position was mainly driven by material and energy requirements (Principle 1) and process characteristics (Principle 2). Indeed, due to the goal and scope of this study, Principles 3 and 4 were not discriminating for this evaluation. The grouping of C2 and C4 was explained by the extra consumptions (water for C2 and diesel for C4), the lack of technology mobility (C2), and the higher number of stages to process the waste (C4). The results did not indicate that advanced technologies (C3 and C4) necessarily represented the technologies with the highest technical degrees (C3 had a technical degree lower than C2). Nevertheless, it is to be noted that given the method used and the recycling solutions

analyzed, the final scores were close to each other and rather central. The detailed ratings for each indicator are provided in Table A2.

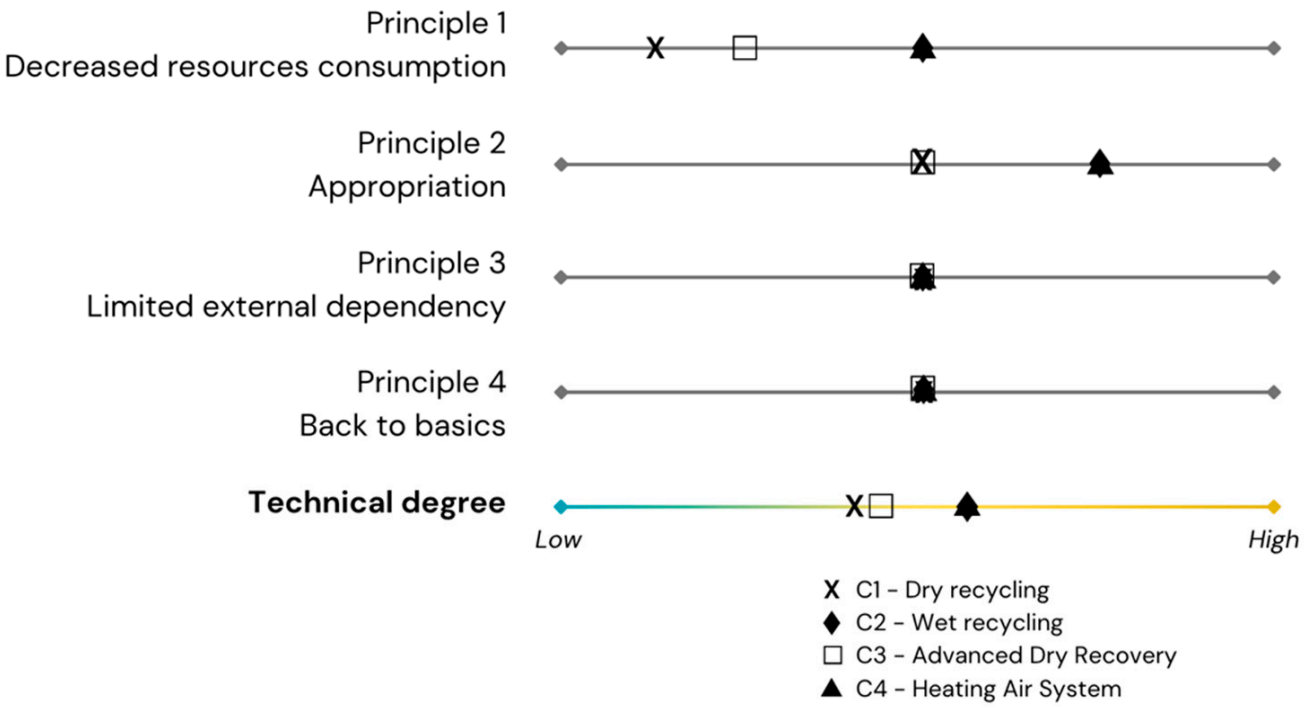


Figure 4. Technical degree in concrete recycling technologies.

3.2. Comparison of Concrete Recycling Technologies Environmental Impact

3.2.1. Environmental Impacts of Concrete Recycling Technologies

As preliminary results, the contribution analysis for each studied technology is presented in Figure 5 (see Table S5 for the supporting figures). Those results showed that for C1, C2, and C3, the transport carried most of the environmental impacts for most of the impact categories. Regarding C4, the HAS processing was the main contributor for most of the impact categories. The environmental benefits due to the avoided products contributed the most to the results for C4. Overall, C2 had the greatest impact, followed by C1, C3, and C4. This ranking showed that there was no correlation between the technical degree and the environmental impact of the studied technologies.

Those results showed, in line with existing LCA studies on concrete and building waste management [1,19,30], that transportation significantly influences the environmental impact results. This point has been highlighted by review papers on waste management, noting that transportation distances are of critical influence [30]. Transportation also drove the results found in [1] and represented between the third and the half of the carbon footprint in scenarios studied in [19]. However, this study focused on the technologies themselves, and the contribution analysis presented in Figure 4 did not enable us to interpret the results regarding the phases directly linked to the technology's choice. To ease this analysis, the transport has been then excluded from the rest of the LCA modeling. The main difference in the results was that the avoided impacts exceeded the generated impacts for almost all the impact categories (83% to 100% of the categories) regardless of the technology. It also slightly changed the ranking: C3 had greater impacts than C1, but C2 and C4 were still the technologies with the highest and lowest impacts, respectively (see Figure S1).

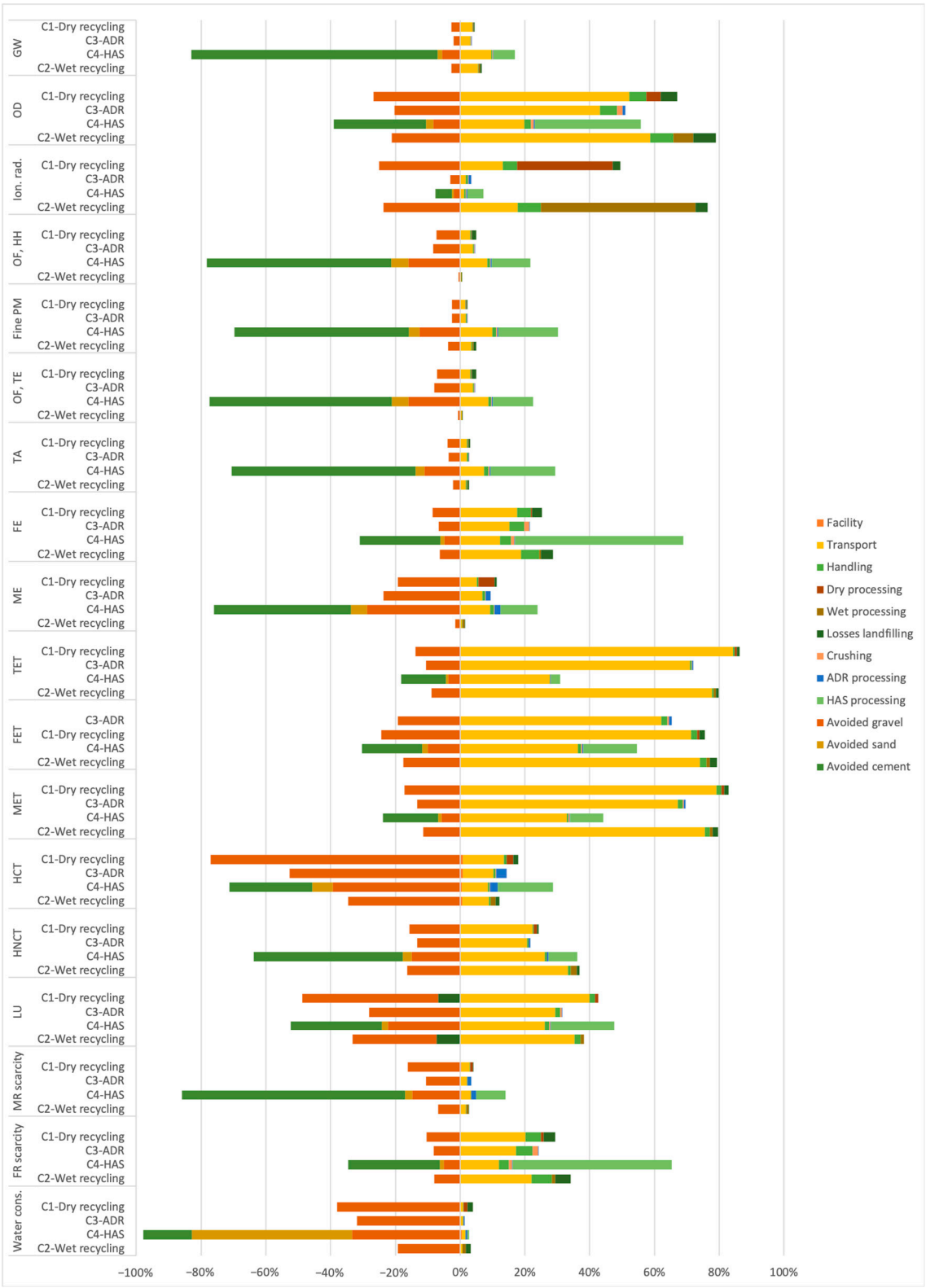


Figure 5. Life cycle assessment results for the four concrete recycling technologies, presented in increasing order of technical degree. GW: global warming; OD: stratospheric ozone depletion; Ion. rad.: ionizing radiation; OF, HH: ozone formation, human health; Fine PM: fine particulate matter formation; OF, TE: ozone formation, terrestrial ecosystem; TA: terrestrial acidification; FE: freshwater eutrophication; ME: marine eutrophication; TET: terrestrial ecotoxicity; FET: freshwater ecotoxicity; MET: marine ecotoxicity; HCT: human carcinogenic toxicity; HNCT: human non-carcinogenic toxicity; LU: land use; MR scarcity: mineral resource scarcity; FR scarcity: fossil resource scarcity; Water cons.: water consumption.

3.2.2. Concrete Recycling Technologies' Environmental Impacts in Regard to the Technical Degree

The comparison results are presented for both the generated and the aggregated impacts: the generated impacts are the direct impacts due to the waste treatment processes; the aggregated ones are the net balance of the generated and avoided impacts. By differentiating the two, we were able to identify the contribution from the technology itself and from the potential benefits provided by secondary material production.

The approach followed consisted of comparing the environmental impacts of one studied technology to another. The couples were created by contrasting the technology with the lowest technical degree, with the one having the highest: C1 vs. C2, C1 vs. C3, C1 vs. C4, C3 vs. C2, and C3 vs. C4. The results are presented in Figures 6 and 7 and should be read as follows: for x % of the pairs (20 in total), the technology with the lowest technical degree (for example, C1) had a much lower/lower/similar/higher/much higher impact than the one with the highest technical degree (for example, C2). For example, in Figure 6a, C1 had a much lower impact than C2 for 45% of the pairs studied (dark green bar) for the Global Warming impact category. It had a lower impact for 20% of the pairs (light green), a similar one for 10% (grey), a higher one for 10% (light red), and a much higher impact for 15% of the pairs (dark red). For simplicity's sake, Figures 6 and 7 present the results for four selected impact categories; the results for all the impact categories are available in Appendix B.

When considering the generated impacts (Figure 6), the results showed that the technologies with the lowest technical degree had lower impacts compared with the ones with the highest technical degree for a majority of couples (4 over 5) and for almost all the impact categories. This conclusion was not true for the C1/C3 couple, for which the results were the opposite: the technology with the lowest technical degree (C1) had the greatest impacts for all the impact categories except for land use.

When considering the aggregated impacts, the same approach led to a bigger variation among the couples (Figure 7). Two couples (C1/C2 and C3/C2) showed that the technology with the lowest technical degree had lower impacts than the one with the highest, and two couples showed the opposite (C1/C4 and C3/C4) for most of the impact categories. There also was a bigger variability across the impact categories compared with the generated impact results, in particular for the C1/C4 and C3/C4 couples. For the first, six impact categories over 18 showed a reversed trend (the technology with the lowest technical degree had lower or similar impacts than the one with the highest), and for the latter, three impact categories were concerned. For the C1/C3 couple, the trend was not clear as six impact categories favored the technology with the highest technical degree, and eight categories favored the one with the lowest.

The reversed trend observed in the pair comparison results between the generated and aggregated impacts was explained with the LCA results. The HAS technology (C4) carried either the highest (generated impacts) or the lowest (aggregated impacts) contribution for most of the impact categories. This difference came from the potential benefits, as C4 allowed for the avoidance of gravel, sand, and cement. It explained why, for the couples involving C4, the tendency was reversed when considering either the generated or the aggregated impacts. For the other couple for which there was a trend inversion (C1/C3), C3 had a lower contribution than C1 for the generated impacts but had also lower avoided impacts, leading to higher environmental impacts than C1 when considering the aggregated impacts.

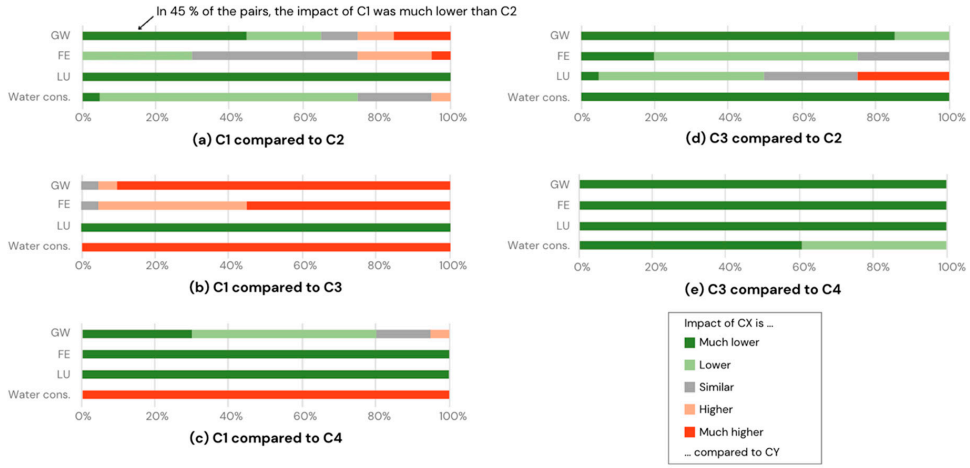


Figure 6. Generated impacts comparison (selected impact categories) for (**a**) C1/C2 couple, (**b**) C1/C3 couple, (**c**) C1/C4 couple, (**d**) C3/C2 couple, and (**e**) C3/C4 couple. C1: Dry recycling; C2: Wet recycling; C3: ADR (Advanced Dry Recovery); C4: HAS (Heating Air classification System).

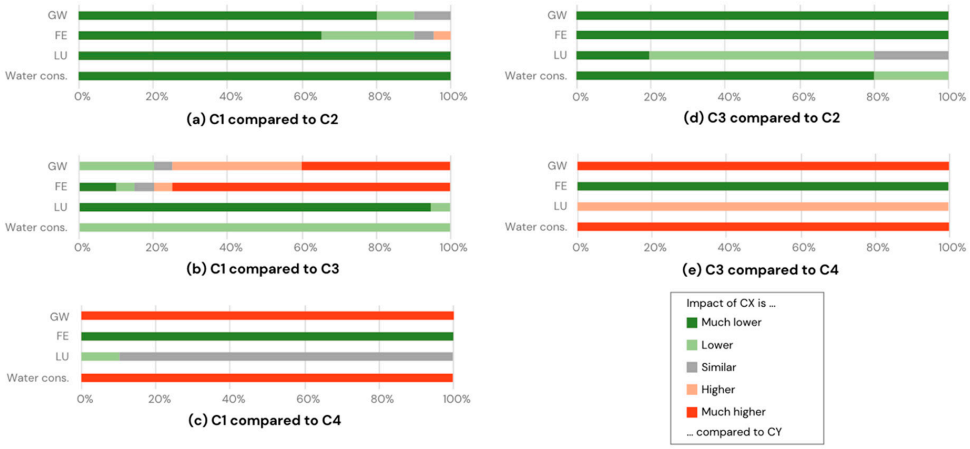


Figure 7. Aggregated impacts comparison (selected impact categories) for the (**a**) C1/C2 couple, (**b**) C1/C3 couple, (**c**) C1/C4 couple, (**d**) C3/C2 couple, and (**e**) C3/C4 couple. C1: Dry recycling; C2: Wet recycling; C3: ADR (Advanced Dry Recovery); C4: HAS (Heating Air classification System).

4. Discussion

4.1. LCA Results

The LCA modeling developed for this study allowed us to ensure the comparability between the technology's alternatives, while the parametrized analysis allowed for the reflection of the variability within each alternative. Nevertheless, due to data availability, some flows (e.g., machinery) were not accounted for each technology. Despite this, the risk of omitting a significant impact source was limited, as the energy consumption associated with the machinery functioning was taken into account for all technologies and all processes, which are the main elements modeled in LCA waste technologies studies [11,23,24]. The prevalence of the avoided impacts in the LCA results can be attributed to the missing data in the LCA modeling combined with the fact that the avoided products were directly modeled from the ecoinvent processes, which could be more exhaustive.

The results showed a trend inversion between the generated and aggregated impacts regarding the technology with the lowest environmental impact. This inversion is due to the consideration, or not, of the avoided impacts in the LCA modeling, in which the generated and avoided impacts are considered on the same level. Indeed, the underlying assumption in LCA modeling is that the secondary products actually substitute virgin products, which

does not necessarily reflect the market reality and the technical constraints of the secondary product uses [31]. The LCA modeling, as currently performed in practice, does not allow for the differentiation of the probability of occurrence of the generated impacts from the avoided ones, which in turn implies that LCA conclusions can favor technologies based on strong uncertain assumptions [31]. Furthermore, the substitution in LCA modeling does not consider the region's use and needs, which can vary depending on the temporal and geographical context [32]. To reinforce the results, further work on integrating technical dimensions and environmental impacts could consider those methodological choices regarding substitution, as they were found to influence the LCA outcomes [31,33,34].

Beyond the modeling issues, the adequacy with the regional context is also reflected in the transportation issues around concrete recycling. The LCA results showed that the transport carried a large part of the environmental impacts (see Figure 5), questioning the relevance of recycling if the materials must be transported, even on short distances. The technologies' mobility thus arises as a lever to mitigate the impacts while answering proximity needs for building sector actors. Further studies could thus consider the variations due to the technology mobility both in the technical degree and the environmental impact assessment (see [1,11] for LCA studies references), allowing us to anchor the approach in a regional perspective.

4.2. Technical Degree Grid

The development of the technical degree grid was the first attempt to qualify waste recycling solutions on a technical scale. It allowed us to put the LCA results in perspective from an angle other than the strict environmental point of view, which is more often considered in waste management studies [13]. This grid allowed us to question the technology in itself, based on technical elements (the Decreased resource consumption and Appropriation principles). It also considered what were the implications of the given technology use (the Limited external dependency and Back to basics principles) that could be of importance in a technology adoption process. Nevertheless, the indicators of those principles were not highly discriminating in this study. It should be noted that in a study with a different goal and scope or with more precise descriptions of recycling technologies and context, ratings for Principles 3 and 4 may differ between the different technologies. These variations in ratings could affect the results by changing the technical degree, but in the case of the more extreme technologies (C1 and C4), it would not affect the LCA comparison results: if C4 had lower ratings for Principles 3 and 4, it would lower its technical degree, but C1 would still have the lowest.

Finally, the number of criteria and indicators varied depending on the principles, and the weighting was set to be equal for each indicator, which can influence the results given the rating methodology. Further discussion on the possible implications of the grid adjustments, as well as their effectiveness in various contexts, is, however, beyond the scope of this study, which focused on how the grid can direct the LCA results interpretation. The next step in the methodological development of the grid could, however, be focused on stabilizing the criteria and indicator selection process by setting broader rules to guide the choices, helping to generalize and reinforce the grid-building procedure.

4.3. Dialogue Between LCA Methodology and Sociotechnical Approach

This study is the first attempt to grasp the environmental impact of waste management technologies from a technical angle. This approach could be included in a decision-making process when it comes to choosing between various technical options. Indeed, the results revealed that some technologies (C1 and C3) have more environmental impacts than others (C4), but they are also the technologies with the lowest technical simplicity and resource consumption. This involves a choice between a strict environmental stance and one that incorporates considerations of, for example, easy-to-repair and sober technologies. Given

that the environmental benefits are allocated to the avoided products that are not necessarily related to local impacts or benefits, the question is also linked to the scale of challenges to address, the sociotechnical approach being able to answer the local needs more directly.

Finally, the approach based on the technical degree could be expanded to include social dimensions, offering a more comprehensive sociotechnical assessment that could be coupled with environmental analysis or other quantitative methods. This perspective could benefit both research and practice by incorporating the social and technical dimensions involved in waste management systems, thus reducing the risk of overlooking key factors in the development of a more sustainable waste industry [13]. The economic dimension could also be included to help go further toward the operationalization of the proposed methodology. It could be more specifically linked with the LCA methodology, as seen in [11,19]. More broadly, systemic and holistic views are called to enhance the transformational potential of the circular economy concept [8,35]. The proposed approach can thus contribute to the successful transition toward circular regions.

5. Conclusions

This study aimed to analyze the concrete waste management alternatives from a technical complexity angle. To this end, a methodology was built to characterize the recycling technologies according to their technical degree, which was defined as a combination of several indicators reflecting the needs in resources, technical simplicity, dependency, and capacity of adaptation. Then, mobilizing the LCA methodology, the potential environmental impacts of the selected technologies were assessed, and a comparison approach was proposed. To do so, the LCA modeling was parametrized to deal with technology variability, and the technologies' impacts were randomly compared by pairs for each technology couple.

The results showed that the technologies with the lowest technical degree tended to have lower environmental impacts than the technology with the highest technical degree when the assessment considered only the generated impacts, with an exception when the technology compared was the one with the highest impacts. When it came to the aggregated impacts, the results were more nuanced, and the less complex technologies had clearly lower impacts for only two couples over five. The results were driven in particular by the consideration of the potential avoided products, which are not necessarily related to local impacts or benefits.

The methodology proposed in this study was a first attempt to approach the LCA results with a technical lens that complements the strict environmental comparison. Further research could develop a stabilized grid-building procedure to enlarge the technical degree assessment. It would help to include social dimensions, offering a more comprehensive sociotechnical assessment to be put in perspective of environmental assessment, thereby enriching it. The proposed approach could also be included in the decision-making process when it comes to choosing between various technical alternatives, especially in a context where the circular economy concept is encouraged to be the new thought pattern.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/recycling10010028/s1. Table S1: LCA inventory; Table S2: Processes used for the LCA modeling; Table S3: Parameter values; Table S4: Couple pairs; Table S5: LCA contribution results; Figure S1: Technologies comparison, no transport.

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Appendix A

This appendix contains details and figures related to the technical degree assessment.

Table A1. Principles, criteria, and indicators mobilized for the technical degree evaluation.

Principle	Criteria	Indicator	Note	Rating Description	Sources
1. Decreased resources consumption	Material consumption [1]	Steel quantity Water quantity	0;1;2 0;1;2	Based on quantitative resource consumptions by technologies: 0 = the less consumptive; 1 = intermediary consumption; 2 = the most consumptive	LCA quantitative data retrieved from literature
	Energy consumption [2]	Electricity quantity Diesel quantity	0;1;2 0;1;2		
2. Appropriation	Technological simplicity [3]	Number of steps	0;1;2	0 = lowest number of steps; 1 = intermediate number of steps; 2 = highest number of steps 0 = mobile; 1 = fixed or mobile; 2 = fixed	LCA quantitative data retrieved from literature
		Type of equipment	0;1;2		
3. Limited external dependency	Upstream dependency [4]	Supplier concentration	0;1;2	0 = low (IHH < 0.1); 1 = medium (IHH 0.1–0.18); 2 = high (IHH > 0.18) 0–50 km = local; 50–150 km = regional; >150 km = national	Grey literature on sourcing of concrete recycling
		Input average distance	0;1;2		
4. Back to basics	Flexibility	Ability to adapt when facing input flow variability (type and quantity)	0;1;2	0 = ability to operate a production shift; 1 = ability to function with reduced input volume; 2 = constant input volume needed	Grey literature on concrete recycling processes; [4]

[1] Material consumption mobilized for the technology production and during its operation. [2] Energy consumption for the technology operation. [3] Number of steps to produce the secondary material. [4] Herfindahl–Hirschman Index (HHI), a measure of the market concentration calculated as follows: $HHI = \sum_{i=1}^{n} s_i^2$, in which n is the number of waste suppliers and s is the share of input, i.e., the share of the total waste received corresponding to each supplier. The share of input is here expressed as a decimal figure (if 50%, 0.5), so the dependency classes are defined as follows: HHI < 0.1 corresponds to low concentration; HHI = [0.1–0.18] corresponds to medium concentration; HHI > 0.18 corresponds to high concentration.

Table A2. Technical degree evaluation.

Principle	Criteria	Indicator	C1—Dry	C2—Wet	C3—ADR	C4—HAS
1. Decreased resources consumption	Material consumption	Steel quantity	0	0	1	2
		Water quantity	0	2	0	0
	Energy consumption	Electricity quantity	1	2	0	0
		Diesel quantity	0	0	1	2
	Principle 1 rating		0.13	0.50	0.25	0.50
2. Appropriation	Technological simplicity	Number of steps	1	1	1	2
		Type of equipment	1	2	1	1
	Principle 2 rating		0.50	0.75	0.50	0.75
3. Limited external dependency	Upstream dependency	Supplier concentration	2	2	2	2
		Input average distance	0	0	0	0
	Principle 3 rating		0.50	0.50	0.50	0.50
4. Back to basics	Flexibility	Ability to adapt when facing input flow variability (type and quantity)	1	1	1	1
	Principle 4 rating		0.50	0.50	0.50	0.50
	Technical degree		0.41	0.56	0.44	0.56

Appendix B

This appendix presents the comparison results for all the impact categories considered in the study.

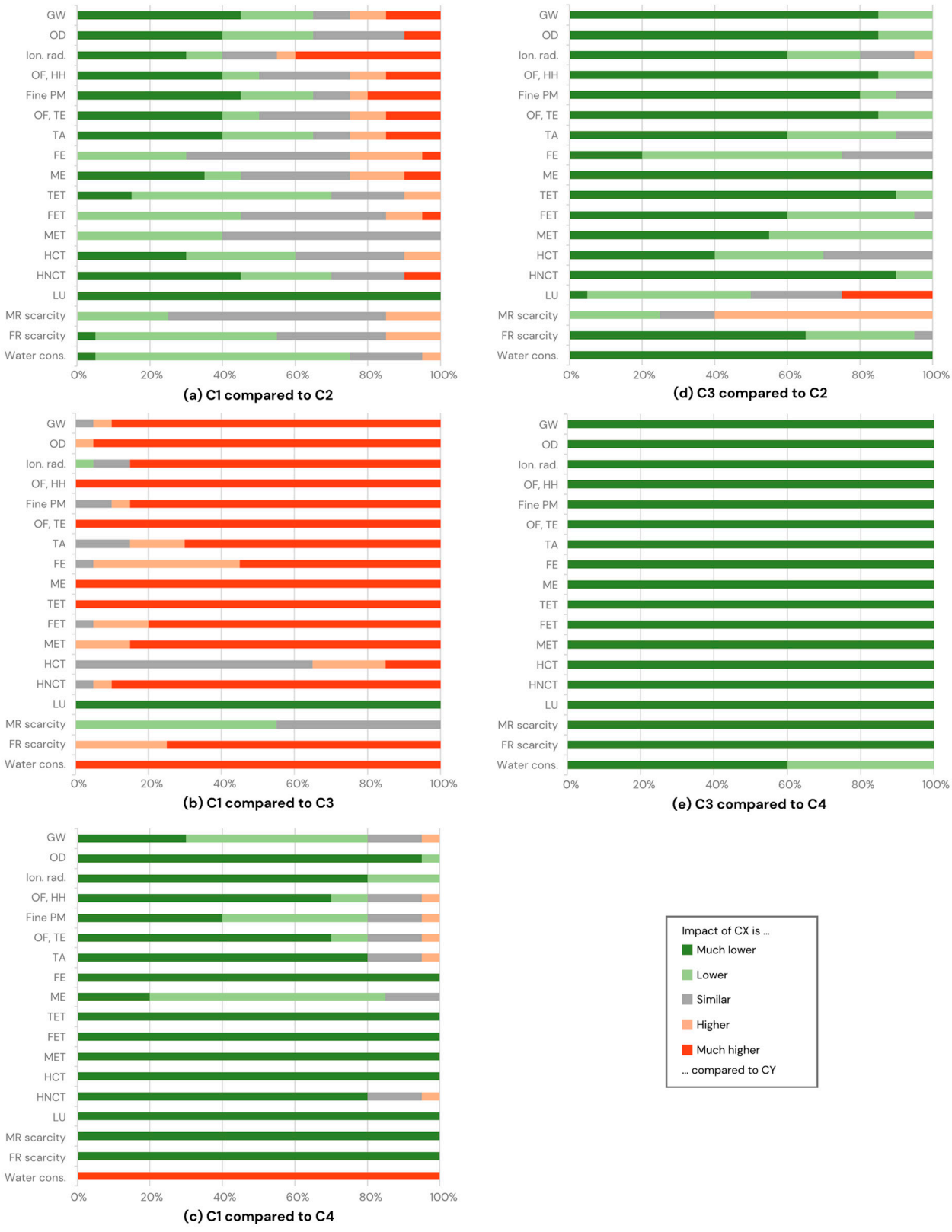


Figure A1. Generated impacts comparison (all impact categories) for (**a**) C1/C2 couple, (**b**) C1/C3 couple, (**c**) C1/C4 couple, (**d**) C3/C2 couple, and (**e**) C3/C4 couple. C1: Dry recycling; C2: Wet recycling; C3: ADR (Advanced Dry Recovery); C4: HAS (Heating Air classification System).



Figure A2. Aggregated impacts comparison (all impact categories) for (**a**) C1/C2 couple, (**b**) C1/C3 couple, (**c**) C1/C4 couple, (**d**) C3/C2 couple, and (**e**) C3/C4 couple. C1: Dry recycling; C2: Wet recycling; C3: ADR (Advanced Dry Recovery); C4: HAS (Heating Air classification System).

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