DOI: 10.1111/jiec.13614

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

RESEARCH ARTICLE

Boosting circular economy solutions in the construction sector using a life cycle assessment

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Editor Managing Review: André Stephan

Funding information
Horizon 2020 Framework Programme, Grant/Award Number: 77675

Abstract

Construction and demolition waste (CDW) management activities have had wide-ranging adverse impacts on the Earth's climate. Addressing the problems of construction and demolition waste production requires a comprehensive and multifaceted approach and specific attention to the development of sustainable circular on-site practices. This study compares recycled products against conventional products already available on the market. This study applied a life cycle assessment (LCA) to evaluate the benefits of secondary raw material (SRM)-based products compared to conventional virgin raw materials. Focusing on a Spanish case study that had foreseen the revitalization of a degraded area, the construction of a small utility building, and road construction, this analysis also assessed the overall environmental footprint of the overall construction work. The results showed that, despite the impact savings achieved by opting for SRM-based products rather than conventional solutions, the production stages still have the greatest impact on the scale of construction, with the sole exception of the construction of small facilities where the construction itself was the largest contributor. Climate change; water scarcity; freshwater eutrophication; resource use, energy carriers; and resource use, minerals and metals were the most significant impact categories both in the analysis of the construction products and the overall construction work. An LCA is vital in the construction and demolition sector because it provides a holistic understanding of the environmental impacts associated with the different stages of a project's life cycle fostering the implementation of circular on-site practices.

KEYWORDS
carbon footprint, circular economy, climate change, secondary raw material, sustainability, waste management

1 | INTRODUCTION

Waste production is one of the most pressing environmental challenges of our time. As the global population continues to grow, urbanize, and consume at unprecedented rates, the generation of waste has reached alarming levels with more than two billion metric tons of waste produced worldwide (Haas et al., 2015). The scale and complexity of this issue, ranging from plastic packaging to electronic waste have far-reaching

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implications for the health of our planet and future generations.

Construction and demolition waste (CDW) production has emerged as a significant environmental challenge (Heeren & Hellweg, 2019). As urbanization and industrialization continue to accelerate, the construction industry has experienced a remarkable boom, resulting in extensive building activities and infrastructure development. However, this rapid growth comes at a cost, generating vast amounts of waste that pose serious environmental and sustainability concerns (Wiedenhofer et al., 2015).

CDW refers to the materials discarded during construction, renovation, and demolition projects. These materials include concrete, bricks, wood, metals, plastics, and various other substances. The magnitude of waste generated is staggering, with construction and demolition activities exceeding three billion tonnes of total waste production worldwide (Gálvez-Martos et al., 2018). The disposal of CDW presents a multitude of challenges. Improper handling and disposal methods can result in significant environmental degradation, including soil, water, and air pollution (Shi et al., 2012). The importance of CDW has been highlighted by the European Commission (EC), which considers CDW one of the five highest priority areas for the circular economy (Domenech & Bahn-Walkowiak, 2019).

Addressing the problem of CDW production requires a comprehensive and multifaceted approach. It involves implementing efficient waste management practices, promoting recycling and reuse of materials, prevention and deconstruction strategies, and encouraging the adoption of sustainable construction techniques. Despite the importance of recycling, prevention and reuse take precedence over recycling according to the hierarchy of actions advocated in the Waste Framework Directive. Thus, to promote reuse and recycling, it is preferable to opt for deconstruction practices rather than outright demolition. By adopting circular economy strategies, the construction industry can minimize waste production, conserve resources, and mitigate the environmental impact associated with construction and demolition activities (Yang et al., 2023).

Life cycle assessment (LCA) has emerged as a valuable tool for assessing and managing the environmental performance of different types of waste such as CDW (Kua & Maghimai, 2017) and food waste (Heller & Keoleian, 2015), and services such as street sweeping (Bartolozzi et al., 2018) and so on (ISO, 2006a, 2006b, 2011). LCA evaluates the environmental impact of a product, process, or system throughout its entire life cycle. It considers all stages, from the extraction of raw materials to the final disposal or recycling of waste, taking into account resource consumption, energy use, emissions, and waste generation (Arvidsson et al., 2018). By applying an LCA to the construction sector, stakeholders can gain insights into environmental hotspots and identify opportunities for improvement (Kim et al., 2018). LCA offers a holistic perspective, considering both direct and indirect environmental impacts, and encourages a shift toward sustainable practices and circular economy principles (Niero et al., 2021).

However, most studies on LCAs provide a stand-alone approach where the focus is on a comparison between linear and circular products, without considering the perspective of the overall construction work. Whether scholars have focused on the environmental impacts of buildings and similar infrastructures, they have not specifically focused on the possible benefits of the circular on-site practices adopted during the construction process. A circular on-site practice aims to minimize waste and maximize resource efficiency by designing products, services, and systems that keep materials in use for as long as possible through different strategies such as recycling, reuse, and regeneration (Geissdoerfer et al., 2020).

In this study, an LCA was applied to assess the overall environmental footprint of the overall construction works represented in a Spanish case study. In addition, an LCA was used to compare the secondary raw material (SRM)-based products produced in the case study against the virgin raw materials that were planned for substitution by the SRM-based products. The case study included the revitalization of a degraded area, the construction of a small utility building, and a road construction. By integrating an LCA into waste management strategies, our study provides useful insights into how to mitigate the environmental impacts of CDW waste, optimize resource utilization, and contribute to a more sustainable and resilient environment.

The upcoming section outlines the current body of literature that our work addresses and introduces the research questions we aim to explore. Section 3 details the data sources and the methodology used for the LCA. Sections 4 and 5 focus on presenting and discussing our findings, while the final section provides a summary of the study's conclusions.

2 | LITERATURE FRAMEWORK AND RESEARCH QUESTIONS

LCAs have been used in waste management for the last two decades and have provided a much-improved holistic view of waste management including waste flows and potential environmental impacts (Vadenbo et al., 2017).

However, over time, LCAs have become extremely common in almost all industrial and service sectors because of their important features (Bartolozzi et al., 2020; Daddi et al., 2017). As shown by Wiprächtiger et al. (2023), LCAs can be used to identify the best strategies or processes to facilitate the transition toward a circular economy (Rieke et al., 2018). Considering that there is still no common agreement among scholars on circularity metrics, LCAs can avoid burdens by shifting from high environmental impact to more resource-efficient consumption. The LCA is recognized by the EC as an official circular economy tool (Marrucci et al., 2019).

With respect to climate change, on the other hand, the use of an LCA is less widespread due to the popularity of the carbon footprint. These two tools have both similarities and differences. On the one hand, they both quantitatively analyze the overall life cycle of the product, service, or organization considering all the inputs and outputs generated during the different phases of the value chain. On the other hand, the carbon footprint limits the assessment to greenhouse gas emissions, thus highlighting only one single environmental impact. The LCA considers 16 different impact categories, including climate change, land use, and water footprint. The LCA, thus, tends to be more complex and resource-intensive than the carbon footprint due to its broader scope and comprehensive assessment methodology (Steubing et al., 2022).

For these reasons, the LCA has become extremely successful in the analysis of waste management strategies and in the development of circular on-site practices. As confirmed by Meglin et al. (2022), CDW has been frequently analyzed using the LCA; however, some gaps still remain. Most related studies have focused on individual environmentally friendly practices, without considering the overall impact of construction work. This study, using an LCA, provides a more holistic perspective on the adoption of circular on-site practices identifying the real benefits and potential trade-offs of circular economy strategies in the construction sector.

An LCA was used by Hart et al. (2021) to identify priorities for reducing the environmental impacts of buildings. The authors demonstrated how best-practice construction activities adopted at sites such as CDW recycling contribute to reducing the environmental impact of the construction sector. By recycling in the cement industry, considerable savings in costs, CO_2, and energy in comparison to conventional cement mixtures using all virgin components are possible. However, before end-of-life treatment, some practices need to be adopted to facilitate recycling.

Selective demolition and recycling have become some of the most common strategies for reducing the impact of CDW (Coenen et al., 2021; Pantini et al., 2019). As shown by Borghi et al. (2018), the decrease in environmental impacts is mostly due to the prevention of landfilling of CDW and the recovery of materials from selective demolition.

Guignot et al. (2015) revealed how the location of supply and demand for concrete production is important, especially in the case of recycled aggregates and pavements. Göswein et al. (2020) claimed that aggregate transport distance is a key factor that determines the cost, energy used, and global warming of mixed recycled aggregates. Attention on transportation was also highlighted by Zheng et al. (2019), who focused on the critical role played by energy used. However, Carpenter et al. (2013) demonstrated that the diesel and electricity consumed by the reuse and recycling of CDW play crucial roles. The energy used in transporting and preparing inert waste for recycling can negate the benefits of recycling.

On the other hand, Pantini and Rigamonti (2020) highlighted that selective demolition may not always be a sustainable choice. Environmental sustainability depends greatly on the characteristics of the building to be demolished, as well as the local markets for recycled materials. Moreover, the benefits of substituting primary raw materials may be negatively affected by increasing impacts due to the additional energy requirements of selective demolition in comparison to traditional methods.

Ventura et al. (2021) assessed the environmental performance of concrete mix designs highlighting the benefits of recycling management practices for enhancing the sustainability of cementitious materials. According to Cao et al. (2018), industrial symbiosis effectively reduces greenhouse gas (GHG) emissions, albeit at a relatively smaller scale than the overall emissions from cement manufacturing. However, recycled concrete aggregates should be considered building materials for road construction, mass concrete works, lightly reinforced sections, etc., although the types and quality of recycled aggregates are crucial in defining their use destination (Džubur & Laner, 2018).

The LCA is recognized as the most powerful tool for assessing environmental performance (Iraldo et al., 2015). As recognized by Gillott et al. (2023), an LCA framework should be used to boost circularity. In addition, since CDW is identified by multiple circular economy policies as a key sector for implementing circularity strategies due to the high volume of waste produced and the large consumption of raw materials, LCA has been frequently used to test the environmental feasibility of recycling CDW and other waste in road pavements. In particular, plastic, glass, carbon fiber, rubber, and even reclaimed asphalt have been found to positively contribute to climate change mitigation as an alternative base in asphalt pavements (Qiao et al., 2020).

Despite the problems that organizations may encounter in the communication of LCA results (Testa et al., 2016), the adoption of LCA-based solutions is crucial to meet the challenges of identifying, improving, and developing circularity indicators (Luthin et al., 2024). LCA enables both scholars and practitioners to focus on different perspectives of CDW and the management of construction work. Pantini et al. (2018) focused on the recycling of asphalt waste through a sensitivity analysis to identify the least polluting technique. Häfliger et al. (2017) examined the environmental implications of recycled aggregate concrete to determine the best mix for recycling waste materials. However, Shan et al. (2019) claimed that the GHG emission reduction potential of CDW recycling might be compromised by other factors. The authors highlighted the importance of the transition to a greener electricity mix to significantly contribute to GHG reductions.

Despite all the benefits derived from recycling activities, as shown by Huuhka and Kolkwitz (2021), circular economy strategies can reduce the construction waste generated. This leads to a potential reduction in the impact caused by the disposal and recycling scenarios.

Scholars have also focused on the overall environmental impact of construction work. Merciai and Schmidt (2018) performed an LCA including all stages of construction products until the final disposal of all residues. The authors suggested that foreground processes, such as concrete manufacture and transportation, contribute significantly to most of the impact results of construction products. Miatto et al. (2022) showed the high environmental impacts of materials and end-of-life stages because of extra transportation needs. However, core material separation in demolition operations and recycling and/or reuse of the material does provide environmental benefits.

Considering that Spain generated approximately 47 million tons of CDW, of which only 13.6% was recycled (Rodríguez et al., 2015), our research contributes to this literature by examining the contribution of the SRM-based products adopted during construction works using an LCA. Many LCA studies are theoretical or based on generalized models. This research, however, applies LCA to a specific, real-world case study. While previous studies might have focused on specific stages of construction or particular materials, this research evaluates the overall environmental footprint of the entire construction work, from production to implementation. This study aimed at developing and demonstrating new circular on-site practices that support companies in setting up successful circular solutions based on waste-to-resource opportunities. Using an LCA perspective, this study offers new perspectives on the possible manufacturing and application of SRMs in building and civil engineering works.

Based on the literature framework described above, this study aims to answer the following questions:

RQ1: Are the SRM-based products for construction works less impactful from an environmental perspective than conventional materials?

RQ2: Considering the overall lifecycle of the construction works, what phase has the main environmental impact?

3 | CASE STUDY PROFILE AND METHODOLOGY

3.1 | Description of the case study

Urban and peri-urban areas, where most construction activities take place, produce large quantities of different waste types. This waste can be a valuable source of locally available SRMs for urban construction work as substitutes for virgin raw materials. This research focused on a Spanish case study as part of the revitalization of a degraded area of 6.000 m^2. The case study took place at the CTC headquarters in Madrid (Spain). CTC Servicios is a company specializing in the management of hazardous and non-hazardous waste that operates in Spain.

The area consists of land that was used to store manufacturing surpluses and raw clay material for the manufacture of bricks for the construction industry. Over time, after the bankruptcy of the company, the factory was abandoned and other CDW was deposited around it. The site turned into an uncontrolled landfill, leading to the consequent environmental and aesthetic problems. The decision to revitalize the area, that is, giving new life to abandoned buildings and degraded areas, was based on environmental, economic, commercial, and technical factors together with visual impacts. More information can be found in the Supplementary Material (Section 1.1).

In the autumn of 2020, the CTC started to create new headquarters within the current CTC facilities to recover space in the old brick factories. The project foresaw the demolition of the kilns and the recovery of the waste to develop new SRMs and use them as new construction products. To facilitate the work and to ensure the best possible recycling opportunities, selective demolition was adopted, separating the CDW as much as possible.

In addition to this CDW, other materials were also used. The rubble produced by the planned demolition of the old kilns and the waste located in the area and from other recycling plants close to the pilot were used to produce new SRMs.

The project also included the construction of a perimetral road of 2800 m^2 for the access and maneuvering of heavy vehicles. The width of the road was 7 m to allow two lanes in parallel, while the length (400 m) began on the access ramp. The plans also included the construction of a small 60 m^2 and 3.8-m-tall facility room for the installation of a basic laboratory and a control room.

3.2 | Functional unit

Since the study was divided into several sub-studies, different functional units were considered. Table 1 shows the different functional units adopted.

The results represent the period between 2020 and 2022. The study reflects the Spanish boundaries; for example, the national grid electricity mix has been used, as well as the specific geographical distances for transport operations. No specific cut-off criteria have been applied to the case study carried out.

3.3 | System boundaries

In this study, construction products were manufactured from several waste streams that were treated with different combinations of physical and chemical technologies. The specific combination of technologies used led to the manufacture of an SRM-based product, which was consequently used to build each construction work.

To better assess the comparative environmental footprint, two different system boundaries were adopted in the LCA. A cradle-to-gate approach was adopted for the manufacturing of the SRM-based products. This covered the environmental impact related to the manufacturing activities involving the extraction of the raw materials until the product was made. A cradle-to-gate approach is appropriate for comparing the environmental performance of SRM-based products against conventional products since the next phases (use and end-of-life) are identical for both SRM-based and conventional products (ISO, 2011).

A cradle-to-grave approach was instead adopted for the overall case study of the SRM-based products. This approach covered the environmental impact related to the whole life cycle of the demo, that is, the extraction of the raw materials, the production of the SRM-based products, and their use in the case study up to the end of life of the materials.

TABLE 1 The functional units of secondary raw materials (SRMs) and SRM products.

Demo description	Unit
Revitalization of degraded area	1 m^2
Construction of a small utility building	1 m^3
Road construction	1 m^2

Identification code	Description	Unit
SRM1	Recycled mixed aggregates composed of concrete and ceramic waste (170107) from the demolition of the kiln	1 t
SRM2a	Recovered clay for fine aggregates	1 t
SRM2b	Recovered sand for fine aggregates using sand waste from several construction works	1 t
SRM3	Recycled concrete aggregates composed of concrete waste	1 t
SRM4	Reclaimed ceramic particles	1 t
SRM5a	Reclaimed asphalt pavement composed of asphalt waste	1 t
P1—Recycled filling for leveling	Leveling layer—Recycled filling for leveling: employed as a naturally graded aggregate for geotechnical leveling of the esplanade, composed of 100% recovered clay (SRM2a).	1 m^3
P2—Recycled filling (geotechnical)	Filling layer—Recycled filling: employed as an artificially graded aggregate for geotechnical leveling of the esplanade, composed of 100% recycled mixed aggregates (SRM1).	1 m^3
P3—Artificial graded with sand recovered	Sub-base course layer—Artificially graded aggregate with recovered sand: employed for the construction of the subbasement of the esplanade, composed of 100% recovered sand (SRM2b).	1 m^3
P4—Asphalt pavement	Pavement layer composed of 100% reclaimed asphalt (SRM5b).	1 m^3
P5—Artificial graded with recycled aggregates	Base-course layer—Artificially graded aggregate with recycled aggregate: employed for the construction of the basement of the esplanade, composed of 100% recycled concrete aggregates (SRM3).	1 m^3
P6—Recycled concrete	Pavement layer—Recycled concrete for flooring composed of unreinforced concrete including 20% of coarse recycled concrete aggregates (SRM3A). This type of concrete is normally employed for massive concrete.	1 m^3
P7—Recycled concrete blocks	Concrete block where 30% of the natural fine aggregates have been replaced by SRM4.	1 m^3
P8—Recycled concrete pavers	Concrete paver where 30% of the natural fine aggregates have been replaced by SRM4, and 100% of the natural coarse aggregates have been replaced by SRM3.	1 m^3

The impact of the construction of the infrastructure needed to process the materials was excluded from both the SMR-based solution and the conventional system. The use phase was not included in the study since the esplanade, facility, and road would not require maintenance throughout their lifespan, which was assumed to be 50 years. For the end of life of the esplanade, only the demolition of the concrete layer (P6) and the artificial graded with recycled aggregates (P5) were considered. For the end of life of the road, only the demolition of the concrete layer and the base coarse layer was considered. For both the esplanade and the road, 99% of the waste will be recycled and the rest will be sent to landfill. For the end of life of the building, only the demolition of the walls was considered. A total of 80% of the building products will be recycled and the rest will be sent to landfill. Figure 1 shows the boundaries of the system.

3.4 | Life cycle inventory analysis

All the input and output data for each process included in the system boundaries were collected in the life cycle inventory. The data were derived for the following life cycle stages.

To obtain SRMs, different processed waste was employed in situ, whereas other SRM and SRM-based products were directly supplied by external waste-recovery firms. Clay waste was modeled considering the movement of the waste and the excavation and loading in the CTC facilities. Part of

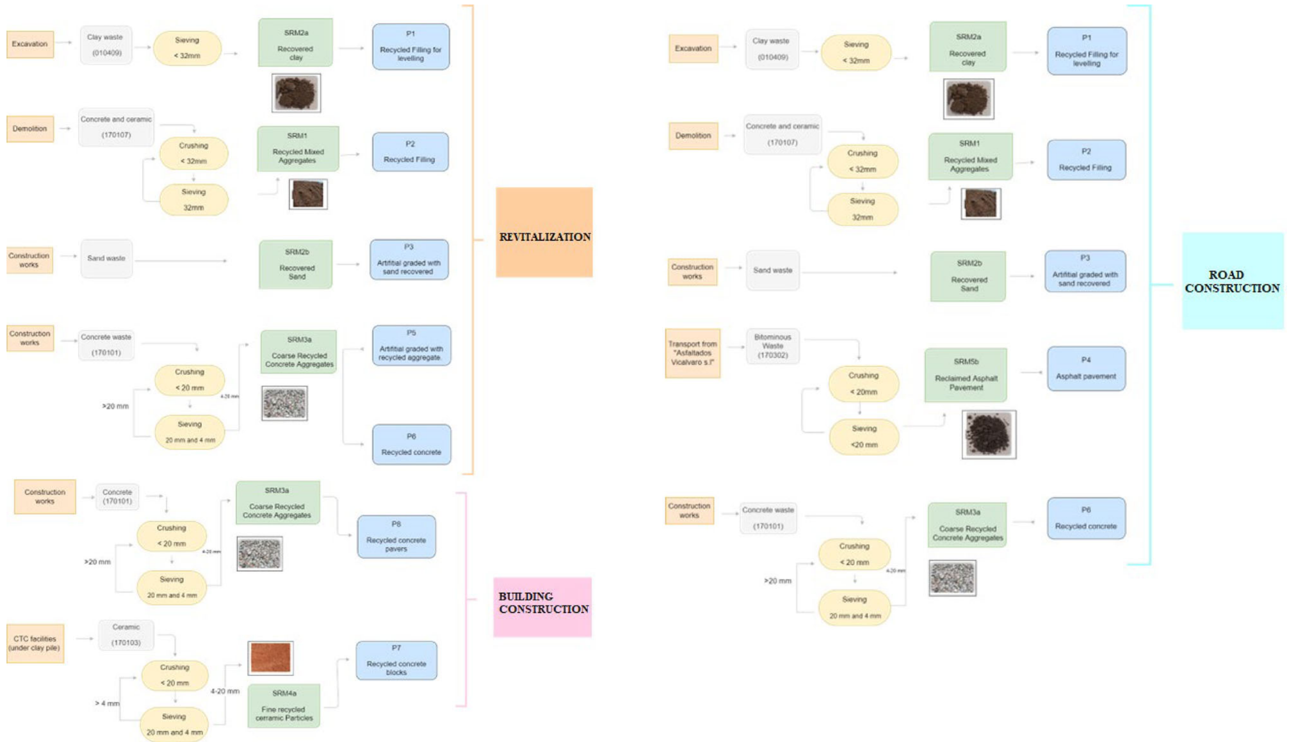

FIGURE 1 Life cycle assessment (LCA) boundaries of the analyzed system.

the waste was sent to the Las Dehesas landfill for use as a waterproofing base. The remainder of the clay was used for the new SRM-based products used in the case study. Sand, bituminous coal, concrete, and ceramic waste were modeled without any input or output since they were obtained were employed directly in situ. However, since concrete and ceramic waste were generated during the demolition of old kilns located inside the CTC facilities, the crushing and remaining operation environmental impacts were considered in the processes related to the SRMs.

SRMs were obtained through CDWs and other inputs (e.g., waste transport, crushing, and sieving processes). Recycled mixed aggregates were modeled using concrete and ceramic waste from the demolition of the old kilns. Diesel and equipment for crushing and sieving were also considered. The recovered clay was modeled using clay waste, diesel, and equipment, for the sieving. Recovered sand was modeled using sand waste from several construction works in Madrid, which were on average 25 km away from the CTC facilities. Diesel and equipment for the collection, crushing, and sieving processes were also considered for recycled concrete aggregates, reclaimed ceramic particles, and asphalt pavements. These three SRMs differed exclusively in terms of material input, that is, concrete, ceramic, and asphalt. In total, eight different SRM-based products were obtained for use in the case study.

If primary data were not used, the data were obtained from the Ecoinvent v.3.7 database. Further details can be found in the Supplementary Material.

3.5 | Life cycle impact assessment

The environmental impact assessment was modeled using LCA Simapro 9 and the ILCD LCA method v. 1.11 (October 2019 version). The ILCD-midpoint 2011 impact assessment method was released by the EC in 2012. The method supports the correct use of characterization factors (to quantify the contribution of different flows to and from a process to each impact category) for impact assessment. The method includes 16 impact categories: climate change (kg CO_2 eq.), ozone depletion (kg CFC-11 eq.), human toxicity—cancer effects (CTUh), human toxicity—non-cancer effects (CTUh), particulate matter (kg PM2.5 eq.), ionizing radiation HH (kBq U235 eq.), ionizing radiation E (interim) (CTUe), photochemical ozone formation (kg NMVOC eq.), acidification (molc Hþ eq.), terrestrial eutrophication (molc N eq.), freshwater eutrophication (kg P eq.), marine eutrophication (kg N eq.), freshwater ecotoxicity (CTUe), land use (kg C deficit), water resource depletion (m^3 water eq.), and mineral, fossil and renewable resource depletion (kg Sb eq.).

All our impact assessment results were normalized and weighted to select the most relevant impact categories to obtain single scores expressed as Eco-milliPoints (mPt), where one point corresponds to the average annual impact of a European citizen. Normalization is defined as "*calculating the magnitude of category indicator results relative to reference information*," while weighting is defined as "*converting and possibly aggregating indicator results*

TABLE 2 The environmental benefits according to single scores for the recycled products compared to those for the conventional products.

Product	Recycled version (mPt)	Conventional version (mPt)	Difference (%)
P1: Recycled filling for leveling versus conventional leveling layer with gravel	0.19	1.20	−84%
P2: Recycled filling versus conventional filling layer with gravel	−2.88	1.56	−285%
P3: Artificial graded with sand recovered vs. conventional sub-base course layer with sand	0.494	1.636	−112%
P4: Asphalt pavement versus conventional base course layer with asphalt pavement	−0.198	11.13	−102%
P5: Artificial graded with recycled aggregates versus conventional base course layer	−3.030	1.416	−314%
P6: Recycled concrete for flooring versus conventional concrete layer	9.533	11.271	−15%
P7: Recycled concrete blocks versus conventional concrete blocks	3.15	3.39	−7%
P8: Recycled concrete pavers versus conventional concrete pavers	2.19	3.39	−35%

across impact categories using numerical factors based on value-choices" (ISO, 2006a, 2006b). In the case of the single score developed by the EC within the framework of the Product Environmental Footprint (PEF) methodology, a set of normalization and weighting factors were used to calculate an aggregated final punctuation. A single score enables an impact to be easily understood and compared with products in the same category and with other environmental impact categories, avoiding impact transfers (Kalbar et al., 2017). The normalization factors represent the total impact of a reference region for a certain impact category in a reference year. Weighting supports the identification of the most relevant impact categories, life cycle stages, processes, and resource consumption or emissions to ensure that the focus is placed on those aspects that matter the most. In this study, we used the normalization factors suggested by Sala et al. (2017), while we followed Sala et al. (2018) for the weighting approach.

4 | RESULTS

The LCA was applied to assess the overall environmental footprint of the full construction works represented in the case study, as well as to compare the SRM-based products, against the virgin conventional materials that are going to be substituted by the SRM-based products.

4.1 | Environmental assessment of the SRM-based products

The recycled filling substitutes for the natural aggregate virgin material (gravel) and performs the same function, without the landfill treatment of the waste used as valuable input in the SRM product. Table 2 and Figure 2 show the total footprint (PEF 16 impact categories—single score) of the comparison. All the results refer to 1 m^3 of product. The detailed results for the 16 impact categories analyzed can be found in the Supplementary Material.

The LCA results show that the adoption of SRM-based products reduces the consumption of natural resources and the environmental load associated with the use of the conventional version. Many factors are related to reducing climate change, thus demonstrating how a circular economy can positively reduce climate change. Sometimes, the results are also negative since the environmental costs associated with the production of conventional materials, which are avoided thanks to the use of SMR-based materials, are much greater than the actual recycling cost. These results showed that not only do SMR-based products have a lower environmental impact than conventional products, but, above all, their use reduces the overall impacts thanks to the avoided landfill disposal of CDW.

The results show that, although all the recycling options perform better, some of them yield better results. In particular, recycled fillings (P1 and P2) exhibited significant advantages in climate change and water scarcity, mainly due to the avoidance of diesel consumed in building machines and water savings for the production of gravel. Significative advantages were also obtained for the SRM-based product in eutrophication freshwater, mainly due to the greater need for electricity from the conventional product, which requires the treatment of spoil from lignite mining attached to the fraction of electricity that uses lignite as a fuel. The same benefits were obtained by the artificial graded aggregate with recovered sand (P3) but in relation to the sand quarry operation and production. However, for resource use, minerals and metals showed significant benefits mainly due to the avoidance of extraction of virgin raw materials, which are replaced by waste input. For resource use, energy carriers, there was a slight

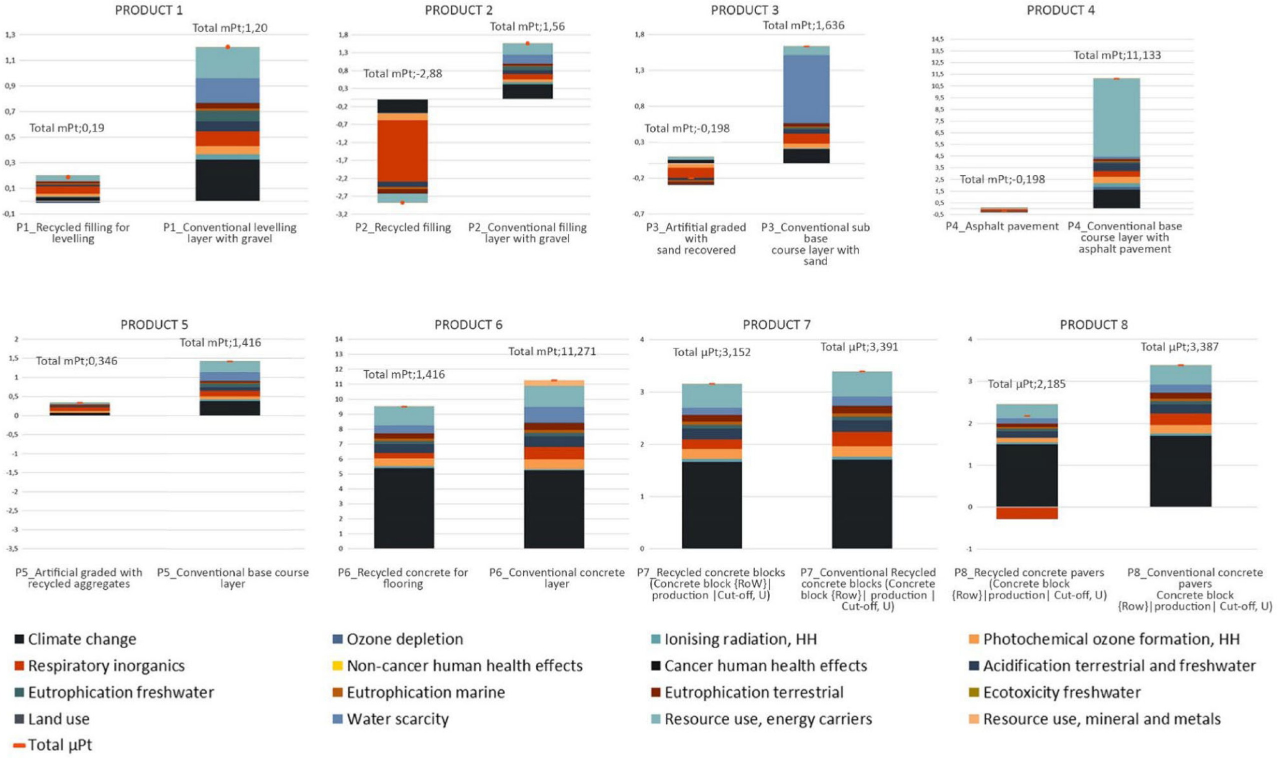

FIGURE 2 Recycled products versus conventional products. Underlying data for this figure are available in Table 2. More detailed information is also available in Tables 35, 37, 39, 41, 43, 45, 47 and 49 of the Supplementary Material.

deterioration mainly due to the diesel used for transporting the recovered sand. Regarding the asphalt pavement (P4), savings were obtained mainly due to the avoided pitch consumed in the bitumen manufacturing, which accounts for approximately 30% of the impact category for the conventional product. Moreover, a significant advantage was obtained in resource use, energy carriers, mainly due to the greater use of petroleum for processing the pitch for the bitumen. The greatest benefits were obtained with the recycled artificial grade aggregates (P5). Avoiding diesel and water consumption, but above all with important savings compared to conventional products (mainly due to the greater need for electricity for the conventional product), led to a reduction of more than 300%.

Finally, P6, P7, and P8 showed drastically fewer benefits. This was because the conventional version also included recycled materials. For P6, the benefits were obtained mainly due to the avoided gravel production for the concrete. For P7, a slight advantage was registered for the SRM-based product in all the impact categories due to the avoided production of sand, while for P8, this advantage was due to the avoided production of sand and gravel. However, our case study increased these benefits, especially in the manufacturing of the pavers, as the quantity of SRM used in the products was greater than that in the blocks.

4.2 | Life cycle assessment of the overall construction work

To answer RQ2, we analyzed all three activities carried out in the case study, that is, the revitalization of the degraded area, the construction of a small facility, and the construction of the asphalted access road. We considered the environmental impact generated along the entire value chain. The detailed results for the 16 impact categories analyzed can be found in the Supplementary Material.

Figure 3 reports the environmental impacts of the activities divided by SRM-based products in terms of manufacturing, construction of the works, and end-of-life.

For the revitalization of the degraded area, the production of SRM-based products was the largest contributor to the environmental footprint, followed by the construction of the esplanade itself and, later, the end-of-life of the esplanade. Most of the environmental impacts were derived from the manufacturing of SRM-based products, the phase that contributes most to nine of the impact categories. However, construction operations were the highest contributors to four of the impact categories (photochemical ozone formation; eutrophication freshwater; eutrophication marine; and resource use, mineral and metals), and the end-of-life phase contributed the most to the Respiratory inorganic impact category.

In contrast, for the construction of a small facility, the construction of the facility itself was the largest contributor to the environmental footprint, followed by the manufacturing of SRM-based products. The construction phase contributed most to six of the impact categories, (ozone

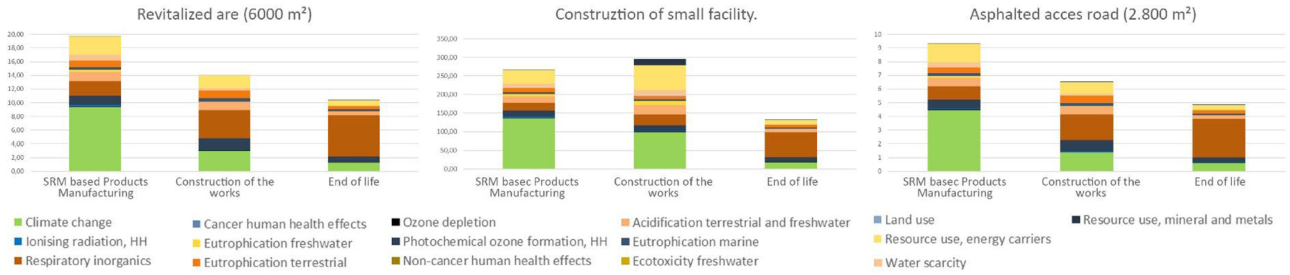

FIGURE 3 Single score results for the three case study activities. Underlying data for this figure are available in Tables 52, 54 and 56 of the Supplementary Material.

depletion; eutrophication freshwater; land use; water scarcity; resource use, energy carrier; and resource use mineral and metals), with the manufacturing of SRM-based products contributing the most to the other six (climate change, ionizing radiation, photochemical ozone formation, acidification terrestrial and freshwater, eutrophication marine, and eutrophication terrestrial). With respect to the construction of the facility phase, the manufacturing of the mortar used and transport to the construction site contribute the most.

Finally, for the construction of the asphalt access road, the production of SRM-based products was the largest contributor to the environmental footprint, followed by the construction of the road itself and later the end-of-life of the road for the revitalization of the degraded area. Most of the environmental impacts were derived from the manufacturing of SRM-based products, which was the phase that contributed the most to eight of the impact categories. However, these works contributed the most to three impact categories (photochemical ozone formation; eutrophication freshwater and terrestrial). The end-of-life phase contributed the most to the respiratory inorganic impact category.

5 | DISCUSSION

We investigated the environmental impact of CDW management, by comparing SRM-based products against conventional virgin products plus the overall environmental footprint of the full construction work. In our case study, the company opted to improve its environmental performance by recovering material from the CDW from construction work.

First, we focused on the environmental benefits of SRM-based products by analyzing their specific contributions. We, then, extended the analysis to overall construction work, that is, the revitalization of a degraded area, the construction of a small utility building, and road construction. In the overall LCA, we considered the manufacturing of the SRM-based products, the construction of the works itself, and the end of life.

5.1 | Managerial implications

Our results showed that the benefits of the use of SRM-based products significantly contributed to reducing the environmental impacts of the overall construction work. Since most of the impact was generated by the production of materials used in the construction works (Figure 3), adopting SRM-based products significantly contributed to the overall reduction of the environmental impact.

All SRM-based products showed a significantly lower environmental footprint than did the conventional systems when analyzing the single score PEF. However, in some impact categories, SRM-based products had a greater impact than conventional products. To reduce the environmental footprint of SRM-based products, some improvements could contribute to reducing the pressures exerted on the environment. In particular, for both the recycled filling for leveling and the recycled artificial graded aggregates, the diesel used in the machinery to process the material contributed the most to the overall impact. An increase in the efficiency of diesel fuel use would reduce the overall footprint. A more significant reduction could be obtained by substituting the machinery with one powered by renewable electricity.

Regarding the artificial graded aggregates with recovered sand and the asphalt pavement, the transport of the reclaimed asphalt pavement to the construction site had the greatest impact. Obviously, reducing the distance would reduce the overall footprint, but above all, the adoption of more sustainable transportation, such as electric trucks, could reduce this pressure.

Finally, for recycled concrete blocks and pavers, the cement and sand used to manufacture the concrete are the most significant contributors to the overall impact. An increase in the efficiency of cement production or the quantity of SRMs used in the product would reduce the overall footprint. Our findings, thus, confirmed Göswein et al. (2020) that recognized the importance of optimized material choice and product design to reach the lowest environmental impact.

Since the adoption of SRM-based products is strictly connected with more sustainable management of the supply chain, in addition to these technical and practical improvements, some governance actions could also be adopted to reduce the overall footprint of construction works. As shown by Daddi et al. (2021), the internalization of environmental management systems positively mediates the relationship between sustainable supply chain management and organizational performance. The use of an environmental management system to assess the environmental performance of construction materials has already been suggested by Dejkovski (2016). The authors claimed that by creating waste indicators from the environmental management system, organizations can better control the impacts of hazardous substances contained in CDW into the ecosphere.

5.2 | Theoretical implications

This study provides empirical evidence that supports the benefits of using SRMs in construction projects. This approach is particularly relevant for scaling up, as it offers a blueprint for broader application in other urban revitalization and construction projects globally. By demonstrating the effectiveness of SRM-based products in a real-world setting, the study provides a solid foundation for their adoption in larger and more complex infrastructure projects. Moreover, the use of novel technologies, such as selective demolition and material recovery processes, facilitates the application of SRMs and underscores the adaptability of this approach across different geographic and industrial contexts. As cities and regions face similar challenges related to resource depletion, waste management, and urban development, the methodologies outlined in this case study can be effectively transferred and adapted to various settings, making it a valuable model for sustainable construction practices worldwide.

The study could also contribute to the development of policies and regulations aimed at promoting the use of SRMs in construction projects. Governments and regulatory bodies could use this evidence to incentivize sustainable practices, such as offering tax incentives or subsidies for using recycled materials or imposing stricter environmental standards on conventional construction materials. However, following the waste hierarchy that prioritizes reuse over recycling, policymakers should support maintenance and prevention activities to avoid demolition.

5.3 | Future research and limitations

Our research has some limitations. In relation to the data, it was not possible to always access the primary data of the producers. Therefore, secondary data were used and this might have generated small biases in the allocation procedures for recycling situations. Moreover, our case study is located in Spain, and a similar analysis conducted in a different country may yield different results due to the national energy mix (Hoque et al., 2012). Other regions facing similar challenges related to land degradation or seeking to revitalize urban areas could benefit from adopting similar approaches. Researchers could use this study as a blueprint for conducting similar assessments in different settings, thereby expanding the body of knowledge on sustainable construction practices. Last, this study did not compare the overall construction works made with conventional materials. Moreover, conventional materials were modeled using secondary data. Future studies may use primary data and extend the analysis to the construction works without limiting the analysis to the product scale.

6 | CONCLUSIONS

We used an LCA to investigate the use of circularity measures within the construction and demolition sector. Since the construction and demolition sector is resource-intensive and generates significant environmental burdens, using an LCA analysis, this study identified the hotspots and the main environmental impacts associated with various stages, such as material production, transportation, construction, and waste management.

By showing that SRM-based construction products have a lower environmental footprint than conventional systems, this study highlights the potential for reducing greenhouse gas emissions, energy used, and resource depletion in the construction sector while boosting circular on-site practices.

Using the LCA as a tool to evaluate different materials, designs, and construction methods, this study selected the options with lower environmental impacts. This study, thus, provides a scientific basis for assessing trade-offs, allowing stakeholders to make more environmentally conscious choices regarding energy efficiency, material selection, and waste management strategies.

The integration of LCA highlights opportunities for further innovation and efficiency in construction processes. This enhances the potential for the case study's findings to inform future policy development, industry standards, and technological advancements in sustainable urban construction.

In terms of future work, life cycle costing could be performed to identify the economic added value provided by circularity initiatives. Circular economy initiatives usually require significant economic investments, thus, boosting the development of tools that could support both private and public stakeholders to efficiently allocate economic resources for the transition toward a circular economy. Future studies could also consider adopting cluster approaches, as suggested by Daddi et al. (2016), in CDW management. To be able to proceed as quickly as possible toward a more circular economy, it is necessary to join forces and collaborate as much as possible. Promoting collaboration between stakeholders for the dissemination of a circular economy culture at different levels and in different contexts is essential for an effective reduction of the pressure exerted by society on the environment.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

On request.

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SUPPORTING INFORMATION

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How to cite this article: Marrucci, L., Daddi, T., & Iraldo, F. (2025). Boosting circular economy solutions in the construction sector using a life cycle assessment. *Journal of Industrial Ecology*, 1–13. https://doi.org/10.1111/jiec.13614