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# LCA of virgin and recycled materials to assess the sustainability of paved surfaces in agricultural environment

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ABSTRACT

The construction sector is currently characterized by high raw material consumption but also by the production of high volume of wastes, mostly constituted by construction and demolition wastes that could be valorized promoting the use of recycled aggregates in substitution of raw aggregates. A promising application for recycled aggregates is for the realization of rural roads and pavements. The agricultural context, characterized by particular type of traffic and need to balance performance and integration with the environment, is suited for the use of these materials for paved surfaces since it can promote, in several cases, the adoption of rural circular processes internal to the farm. However, if on one hand the adoption of recycled aggregates could increase the sustainability of the sector, on the other it could increment the environmental loads if the whole process is not properly organized. For instance, the negative effects of transportation operations can cancel the environmental benefits if high distances between the production and the destination sites are present. This work reports the results of the Life Cycle Assessment (LCA), from cradle-to-gate, of four different construction aggregate classes that can be used for the realization of rural roads, pavements and forecourts, and paved areas in agricultural environment. The first three materials are recycled aggregates produced by the recycling processes of construction and demolition waste and the fourth type refers to gravel aggregates produced from natural resources. The Life Cycle Assessment was realized using site-specific primary data from the local territorial context and paying particular attention to transportation-related impacts, land use, avoided landfill and preservation of non-renewable resources. The results of the work clearly show that the environmental impacts in both scenarios of recycled aggregates are lower than the virgin aggregate scenario. In fact, considering the midpoint categories, the recycled materials proved to be more virtuous in almost all the indicators, with the exception of the marine eutrophication. The most significant gap between virgin and recycled materials has been in global warming and marine and freshwater eco-toxicity.

## 1. Introduction

Currently, the realization of paved surfaces is characterized by a significant consumption of raw materials, such as non-renewable bulk resources and, at the same time, is also responsible for significant waste streams (Faleschini et al., 2016; Garcia et al., 2016). The construction material section is equal to 3–4% of the total industrial production in Europe, and the construction industry, as well as construction works, involve millions of employees (Oikonomou, 2005) However, in the same way, the construction sector is responsible of the consumption of 50% of natural raw materials, 40% of the total energy produced, and produces more than 50% of total inert waste (Anik et al., 1996). In the European Union, the annual generation of construction and demolition (C&D) waste is about 850 million tonnes (Tojo and Fischer, 2011; Zhang et al., 2020) and improper management of construction and demolition wastes (C&DW) often results in considerable environmental impacts. Considering alternative management routes could result in both environmental and cost savings (Institute for Environment Sustainability, 2011). The C&D material consists in one of the most voluminous streams of waste generated in the world, rating for about 25–30% in mass of the whole waste production (Cerminara and Cossu, 2018). This type of waste is mainly inert and is constituted by aggregates with limited amount of other components, such as steel or wood, which depends on the source of the waste and the related working practices (Colangelo et al., 2022). Despite the significant potential of recycling C&DW for the aggregate market, a large part of C&DW are disposed in specific landfills, with a

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consequent high increase of the ecological footprint of the construction industry Irshidat et al., 2021.

Another limiting aspect in the usage of recycled aggregates (RA) is the difficulty to standardize the evaluation of recycled aggregate quality. In fact, this last can be lower than quality of virgin natural aggregates (NA) and could be caused, for instance, by unsuitable treatments and processes or by the poor mechanical properties of some components in the mixture or by the presence of particular contaminants (Faleschini et al., 2014; Fathifazl Abbas and Foo 2009; Pepe et al., 2014). The target for the recycling of these materials, defined by the European Union in the Directive 2008/98/EC, is set to a minimum of 70% by weight before the end of 2020 (European Commission, 2008) and the Italian percentage is respecting this set quantity (Cárcel-Carrasco et al., 2021). Despite this, based on the statistics reported in (Blengini and Garbarino, 2010), in the 2010, about 80% of the inert waste was landfilled. Based on data until 2018, in Europe, the level of recycling and material recovery of construction and demolition waste varies consistently across the countries, ranging from less than 10% to over 90%. Despite this, RAs are interesting and valuable resources that could be used for several civil applications, based on their quality and properties (Irshidat et al., 2021). In fact, they could be used for environmental filling and rehabilitation of depleted quarries and landfills, in road works as sub-base (Marinković et al., 2010), base or unbound material, as granular bedding or filter material for drainage layers, and in concrete production as paving block, pedestrian paving slab, curbs, roads meridians, anti - barriers, railway platform, mass concrete applications (e.g. bridge abutments, seawall blocks, shore protection works), and high grade applications (e.g. precast elements) (Ding et al., 2016; Pešta et al., 2020; Bastidas-Martínez et al., 2022). A promising area for the use of these recycled materials is the construction of rural roads and pavements. In fact, in rural and sub-urban areas, agricultural activities and services play a crucial and multifunctional role which requires proper design not only of rural roads but also of the outdoor areas of farms (Pourkhorshidi et al., 2020). Moreover, these agricultural structures must be stable under all static and dynamic loadings during construction and in service (Z. Hossain, 2013). An important solution is using strong or treated subgrade to provide the required thickness of a flexible pavement by a reduced thickness, as compared to untreated and weaker subgrades (Rachmawati et al., 2018). This choice will therefore result not only in an increasing durability but also in a significant cost saving advantage (Choudhary et al., 2010). In fact, a well-known technique is the replacement of soil with stronger material such as crushed rock or stabilized materials such as recycled materials. The sustainability of the solutions should become a central pivot of the corporate and territorial strategies in rural areas. These pavements must respond to a variety of requirements and properties, which make them a topic under increasing study and development. In these areas, the interest is to develop low-impact solutions, which combine the obvious structural and functional requirements with environmental and landscape protection requests Tang et al., 2022. In addition most of the existing codes, guidelines and regulations fix strict barriers for the maximum allowable quantities of RAs (Rugarli, 2018; DIN 1045-2:2008, 2005; BS EN 206:2013+A1:2016 2013). Besides the technical requirements, which may limit their use, environmental aspects related to the release of dangerous substances to air, soil, surface water and groundwater, particularly with respect to leaching potential (Hjelmar et al., 2013; Zhang et al., 2020), must be take into account.

A critical aspect highlighted by some researchers, is that energy consumption of the recycling process can be higher than the energy requested for the disposal in landfill, which, with the transportation, could rise the environmental impact of this type of aggregates (Marinković et al., 2010; Blengini and Garbarino, 2010). Despite these negative aspects, generally processing and recycling of C&DW into new second raw materials can allow to obtain relevant environmental positive effects, e.g. landfill avoidance of inert waste and the non renewable resources preservation (U. Hossain et al., 2016). In particular, the NA supplying processes consider a panorama of direct and indirect impacts that could be reduced and mitigated by the use of recycled products (Pešta et al., 2020). To evaluate the positive effects of the recycled aggregates, a Life Cycle Assessment analysis (LCA) (Finkbeiner et al., 2006) could be performed to compare the environmental performance of recycled-based and virgin natural-based materials and to provide useful information for the selection of the most environmental friendly materials (Colangelo et al., 2020). Following this approach, for example, Faleschini et al., 2016 compare the environmental impacts of virgin and recycled products provided by the same case study plant. The work underlines the importance of implementing renewable energy in this type of processes that allow to limit the impacts related to the energy consumption or compensate the most negatively impacting processes such as transportation as explained in Estanqueiro et al., 2018; Yazdanbakhsh et al., 2018. This work reports the results of the LCA, from cradle-to-gate, of three different recycled aggregate materials that can be used in the construction sector for the realization of rural pavements and rural forecourts compared with the virgin aggregates with identical application. The first three materials are recycled aggregates produced by the recycling processes of construction and demolition waste and the fourth type refers to gravel aggregates produced from natural resources. The LCA was realized using site-specific primary data from the local territorial context and paying particular attention to transportation-related impacts, land use, avoided landfill and non renewable resources preservation. This work allows to quantify and compare the environmental impacts of the four different aggregate classes and can be used to properly select the most environmental-friendly mixture, for the construction of rural pavement. Moreover, it can help choosing the low impact material may be for road construction in the rural sector.

## 2. Materials and methods

The LCA methodology is commonly used to quantify and analyse the environmental impacts of any product or service through the life cycle phases. The structure of the analysis is defined in (European Standard Commision, 2006a, 2006b) and, firstly, the objectives of the study, the functional unit, the system boundaries, the impact assessment methodology must be defined. Then, life cycle inventory analysis (LCIA) takes into consideration all relevant inputs and outputs of each unitary process. Finally, the impact assessment quantifies the potential environmental impacts and possible consequence on human health, according to the selected impact categories and the corresponding characterization models, and assigns the LCI results to the impact categories. Finally, the results of the analysis are interpreted and use as decision-making tool in order to score the different materials.

### 2.1. Goal and scope

The LCA has been conducted to compare the environmental impacts of different materials for the construction of a rural pavement. The main focus has been assessment of the different impacts of the constriction materials (recycled products and virgin natural products), for paving a working area in a farm. For the recycled materials, the data are primary data collected in a company, the C.A.R. facility located in Imola (North of Italy). In particular, three different recycled materials have been considered to be compared to virgin aggregates: recycled stabilized cement, recycled stabilized cement and asphalt and recycled ground stone. All the materials have the physical and mechanical properties to be used in secondary rural roads and livestock pavements. This information explains the functional unit determined in this study: volume of material ($m^3$ of mixture) necessary for the construction of 10 m of a rural pavement. In particular, the volume of 10.5$m^3$ used for the realization of a road segment 10.0 m long, 3.5 m wide and 0.30 m depth has been considered. In the models of the recycled aggregates, a physical allocation method was used, considering the presence of valuable co-products in the production, as better explained in the life cycle inventory section (see Section 2.3). The analyses have been conducted in OpenLCA 10.1, taking Ecoinvent 3.6 database as a reference to configure the inventory of minority materials (i.e. fuel, electricity, machine operations) and the virgin natural aggregates production model.

### 2.2. System boundaries

The investigated materials have been modeled from the production phases to the preparation and construction of the above-said partial road. Then, the environmental impacts analysis of the four selected materials, has been based on a "from cradle to gate" approach. Fig. 1 shows the scheme of the model with the system boundaries for two different processes: the first (see Fig. 1(a)) is related to the NAs whereas the second is related to the RAs.

In Fig. 1(b), i.e. process B, waste inert in input has been highlighted because two different modeling approaches were used.

Two different models have been carried out for process B:

1. The waste materials enter into the systems as raw material without previous environmental burdens (model 1);
2. The waste materials have been removed from the disposal chain, assuming the role of avoided wastes (model 2).

In practice, with the second approach, the system boundaries related to the recycled product process has been also considered in an expended prospective. This dual modeling approach does not affect process A, which remains unchanged, while it could give a better prospective of the sustainability of the investigated recycled materials. The three recycled materials have different origin and different production process, in terms of both phases and working time. In particular, from the information collected in the company, it was possible to determine the detailed operations referred to the input waste materials treatments Table 1 schematically presents the operations considered in the study. A specific combination of these end-of-waste materials, in different percentages, provides the final recycled products, as is presented in the section below.

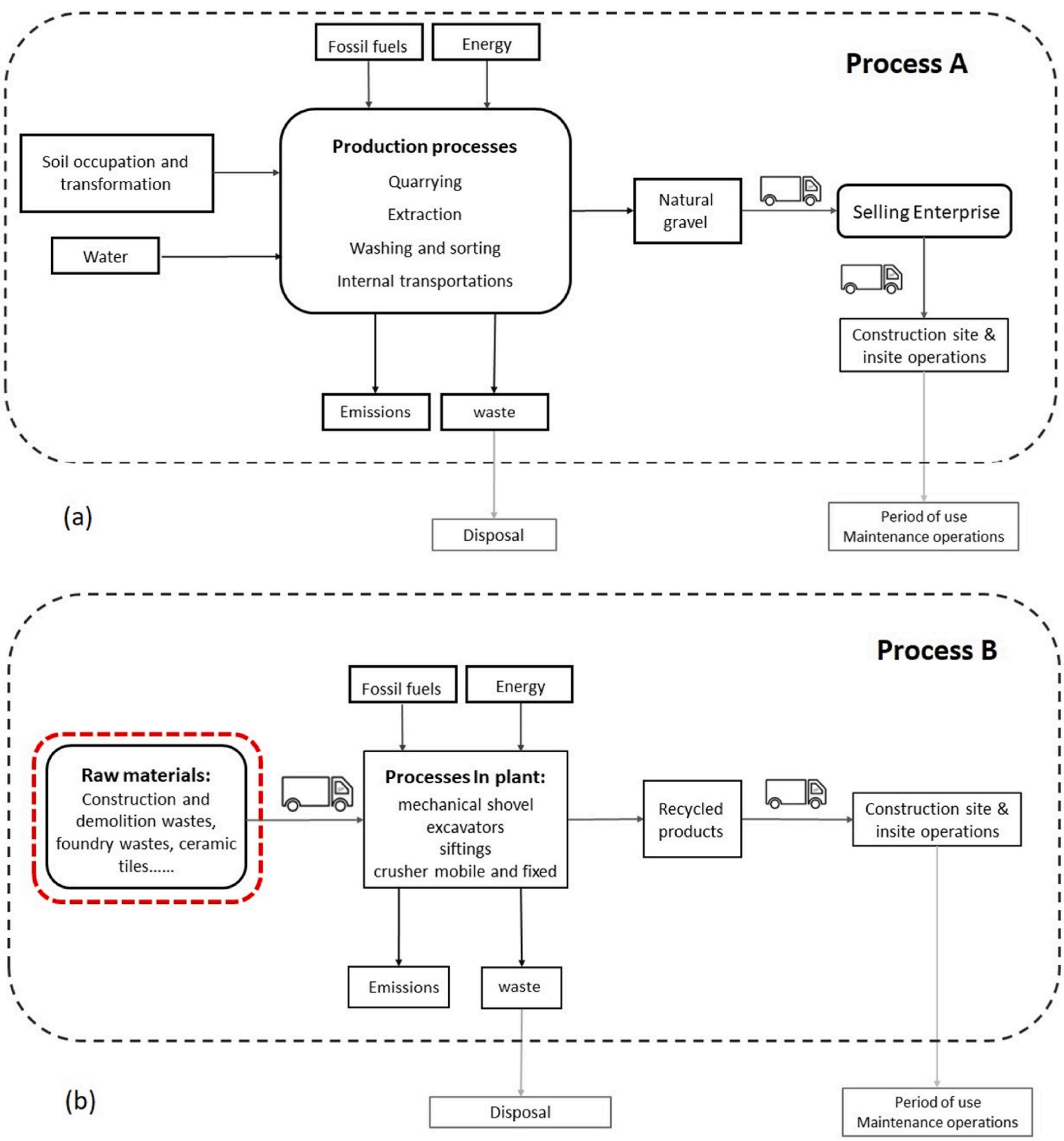


**Fig. 1.** System boundaries for Process A (above) and Process B (below).

**Table 1**
Necessary operations for the recycling of the incoming waste in the enterprise.

| | asphalt | generic demolition waste | inert demolition waste | ceramics | foundry waste |
|---|---|---|---|---|---|
| manual sorting | × | × | × | × | × |
| transport to electric mill | × | × | × | × | × |
| grinding | × | × | × | × | × |
| manual sorting | × | × | × | × | × |
| screening (3 sifts) | × | × | × | × | × |
| regrinding of the remains | × | | | | × |

### 2.3. Life cycle inventory

The LCI was performed following all the steps of the ISO 14040–44 (European Standard Commision, 2006a,b). The data for the three recycled materials have been collected directly from the case study plant.

Primary data about the elementary flows of the preparation and processing of aggregates phases, have been calculated starting from the productive processes of the enterprise, where the C&DW recycling takes place in a stationary plant. In particular, the facility selected as representative case study, has an area of 45.000 $m^2$ with an average amount of processed wastes of 177,000 tonnes per year and a production of recycled product of about 142,000 tonnes per year (calculated on the basis of the last three years). The plant produces recycled materials of both mono-waste species and mixture of few species with different characteristics and particle size. The three recycled materials investigated in the works have similar characteristics, and are proper for the function defined. Based on the information from the company, these recycled materials are an important part of the annual production and they are characterized by different wastes or different incoming proportion of the wastes, as raw materials:

- **Recycled stabilized cement (RSC)**, a recycled waste based on concrete/cement waste, with a diameter of 0/30 mm, based on a double grinding process, which is the 8% of the global production of the plant;
- **Recycled stabilized cement and asphalt (RSCA)**, a recycled waste based on concrete and asphalt waste, as a 50-50% mixture with a diameter of 0/30 mm, based on a double grinding process, which is the 4–6% of the global production of the plant;
- **Recycled ground stone (RGS)**, a recycled waste based on mixed waste with different percentages: generic demolition waste at 50%, ceramic/tiles at 30% and foundry waste at 20%. This material has a diameter of 0/30 mm, based on a double grinding process, which is the 18% of the global production of the plant.

The enterprise has provided annual data on production, operations, processes, inputs (incoming waste, electricity and fuel) and transportation with the relative reference distances, for the period 2018–2019, as shown in Table 2). In particular, the data on mills operations and energy/fuel consumption have been attributed to the different products, based on the data on productivity per hour or working time collected from the company (see Table 2).

Instead, the handling phase of the materials, inside the plant area, have been considered similar for the three products. In the processes, the water consumption for the whole products, has been neglected in consideration of the limited amount of water used in these processes.

The primary data about transport types and distances provided by the C.A.R. company are reported in Table 3. The demolition wastes, concrete wastes, ceramic and asphalt wastes come from an area with a radius of about 40 km, on the other side the industrial (foundry) wastes come from a distance of about 250 km. GIS data, from the regional database, have been used to determine instead the origin of the virgin natural aggregates. Then, the distance between the quarrying site of these resources and the plant has been defined equal to 60 km. It is worthy to remind that the processes to produce recycle materials return several co-products besides the main product. This aspect has been considered in the models applying and allocation method for the impact based on a physical approach. This means that the environmental impacts due to the production phases have been assigned to the different products based on the amount produced. Therefore, even in this case, several co-products and by-products are carried out during the production of the three main products under investigation, as shown in Table 4. Moreover, some wastes are present in the recycling process, such as wood pieces, plastics or glass, whose disposal phase is not part of the system boundaries. The co-products and by-products of RSCA and stabilized cement process productions are similar since both are a mixture of cement as main compound. In the study, the distance between plant and construction site has been considered constant and equal to 15 km for all the four materials.

**Table 2**
Life Cycle Inventory of the three recycled materials.

| Production Data | Amount | Unit |
|---|---|---|
| Total production of the plant | 142000 | t/y |
| Total amount of incoming materials | 195000 | t/y |
| Electric mill energy consumption | 112945 | kWh/y |
| Offices energy consumption | 50000 | kWh/y |
| Wheel loader working time | 1500 | h/y |
| Excavator working time | 1000 | h/y |
| Mobile mill and vibrating screen working time | 600 | h/y |
| Electric mill working time | 800 | h/y |
| Fuel consumption for plant machine | 115936 | l/y |

### 2.4. Life cycle impact assessment

The impact assessment analysis has been conducted based on two impact assessment methods: Recipe 2016 (H) (midpoint and endpoint) and IPCC 2013 GWP 100a. The Recipe 2016 method was born from the combination of the CML-IA method and the Eco-Indicator 99 method (one of the first developed by the European Union), and has 18 different midpoint and 3 endpoint indicators, and is often used on a global scale. The methodology considers different perspectives, which group similar types of assumptions and choices. In this case, the hierarchy perspective has been selected, based on scientific consensus with regard to the time frame and plausibility of impact mechanisms, as explained in Huijbregts et al. (2016). The 18 midpoint impact categories are: Acidification, Fine particulate matter formation, Fossil resource scarcity, Fresh water aquatic ecotoxicity, Global warming, Human health, Ionizing radiation, Land use, Marine aquatic ecotoxicity, Marine eutrophication, Mineral

**Table 3**
Data about transports of the inputs materials, virgin and recycled, and distance of the construction site.

| Input | Type of transport | | Distance | Unit |
|---|---|---|---|---|
| Demolition wastes Concrete wastes Ceramic tiles Asphalt waste | Transport lorry EURO | 5 | 40 | km |
| Foundry wastes | Transport lorry EURO | 5 | 250 | km |
| Quarrying site for virgin aggregates | Transport lorry EURO | 5 | 60 | km |
| Construction site | Transport lorry EURO | 5 | 15 | km |

**Table 4**
Products and Co-products of the recycling processes of the materials considered.

| Ground stone production process | | |
|---|---|---|
| Product | Percentage | Amount (t/h) |
| Ground stone (0–30) | 50% | 115 |
| Concrete breach (40–80) | 30% | 69 |
| Grit | 10% | 23 |
| Iron | 10% | 23 |
| **Stabilized cement production process** | | |
| Product | Percentage | Amount (t/h) |
| Stabilized cement (0–30) | 40% | 28 |
| Concrete breach (40–80) | 58% | 40.6 |
| Grit | 1% | 0.7 |
| Iron | 1% | 0.7 |

resource scarcity, Marine aquatic ecotoxicity, Ozone depletion, Ozone formation (Human health), Ozone formation (terrestrial ecosystems), Terrestrial acidification, Terrestrial ecotoxicity, Water use. Then, the endpoint indicators are Damage to human health, Damage to ecosystems and Damage to resources availability. Additionally, the carbon footprint of the cases under study have been calculated by the IPCC 2013 GWP 100a method, as additional endpoint indicator of the climate change impact of the whole processes involved.

## 3. Results and discussion

The results of the impact analysis, related to the 18 categories of the ReCiPe 2016 method, are reported in Table 5, including process A and both scenarios of process B. In general, the four materials under study have similar impact values in just few categories: freshwater eutrophication, stratospheric ozone depletion and mineral source scarcity. Instead, most of the categories show considerable differences, not only between different materials, but also between the different modeling approaches used for a single recycled material. Among them are to cite: ozone formation, human health and terrestrial ecosystems, and terrestrial acidification. Considering for the recycled aggregates the average impact results from the two approaches, the RGS material demonstrates to have the lower impact value in these categories:

- ozone formation, human health, RGS has the lowest impact, with 21.6 kg NOx eq less than RSCA, 20.3 kg NOx eq less than RSC and then, 37.84 kg NOx eq less than NGA.
- ozone formation, terrestrial ecosystems, where RGS has the lowest impact, with 22.14 kg NOx eq less than RSCA, 20.84 kg NOx eq less than RSC and then, 38.8 kg NOx eq less than NGA.
- terrestrial acidification, where RGS has the lowest impact, with kg 15.3 $SO_2$ eq less than RSCA, 14.95 kg $SO_2$ eq less than RSC and then, 28.34 kg $SO_2$ eq less than NGA.

Fig. 2 reports the results of five categories for the four different materials. Fig. 2(a) shows the comparison between Process A and model 1 of Process B while, Fig. 2(b) shows the comparison between Process A and model 2 of Process B. In this approach, RGS shows to have lowest environmental impacts in terms of land use, ionizing radiation and human carcinogenic toxicity. Comparing this solution with the natural aggregates option, the solution with recycled material has about 20% reduced impacts. Instead, in terms of marine ecotoxicity and freshwater ecotoxicity, the recycled stabilized cement has the best performance. In the second model of process B, the RGS shows globally the lowest environmental impacts, between the 13 and 20%.

Fig. 3 reports the results of other four categories for the four different materials. Fig. 3(a) shows the comparison between Process A and model 1 of Process B while, Fig. 3(b) shows the comparison between Process A and model 2 of Process B. In Fig. 3(a), the RGS shows the lowest impact in two of the three categories: water consumption, global warming and fuel resource scarcity. Instead, the RSC reports the lowest impact in terms of human non-carcinogenic toxicity. On the contrary, Fig. 3(b) shows that RGS material has the lowest impacts in the four categories.

The results of last two categories of Recipe midpoint method - fine particulate matter formation and marine eutrophication - are shown in Fig. 4. Fig. 4(a) shows a peculiar result related to the Model 1 where the inert recycled materials have been modeled as avoided wastes. In fact, the recycled stabilized cement and asphalt show a negative value that corresponds to an avoided environmental impact. Considering the fact that this recycled material is a 50% blend of recycled asphalt and RSC - which, as single product, does not show the same behavior - the avoided impact depends on the removal of asphalt from the disposal chain. On the contrary, the other products present positive similar, albeit limited, values of impact, in both modeling approaches. Considering the model 2, the RGS confirms to have the lowest impacts and, in this case, the case with the recycled product, RSC presents a value of kg of nitrogen equivalent slightly higher than the case with natural aggregates.

Fig. 4(b) shows the results of the fine particulate category where the case with RGS confirms to have the lowest impacts, compared to the other materials, in both modeling approaches. In particular, it has from 16 to 22% lower values of particulate emissions (kg PM 2.5 eq).

**Table 5**
Impact assessment values calculated for the ReCiPe 2016 midpoint (H) method.

| Categories | Model 1 | | | Model 2 | | | |
|---|---|---|---|---|---|---|---|
| | RGS | RSCA | RSC | RGS | RSCA | RSC | NGA |
| Fine particulate matter formation (kg PM2.5 eq) | 69.58 | 75.07 | 75.45 | 66.2 | 74.54 | 72.9 | 80.64 |
| Fossil fuel scarcity (kg oil eq) | 21849.93 | 23540.74 | 23641.81 | 21150.73 | 23448.93 | 23362.56 | 25216.06 |
| Freshwater ecotoxicity (kg 1,4-DCB) | 1455.21 | 1570 | 1578.42 | 1414.61 | 1429.67 | 1145.89 | 1688.6 |
| Freshwater eutrophication (kg P eq) | 4.67 | 5.04 | 5.07 | 4.5 | 5.018 | 4.83 | 5.53 |
| Global warming (kg $CO_2$ eq) | 63560.64 | 68593.4 | 69005.55 | 61689.54 | 67422.36 | 68056.53 | 73399.08 |
| Human carcinogenic toxicity (kg 1,4-DCB) | 1313.56 | 1422.13 | 1433.1 | 1269.85 | 1398.8 | 1342.34 | 1532.16 |
| Human non-carcinogenic toxicity (kg 1,4-DCB) | 37122.83 | 40089.14 | 40373.27 | 36091.43 | 39673.11 | 25481.20 | 42941.56 |
| Ionizing radiation (kBq Co-60 eq) | 1471.38 | 1585.68 | 1593.85 | 1434.02 | 1577.98 | 1558.86 | 1736.47 |
| Land use ($m^2$ a crop eq) | 1983.26 | 2139.65 | 2150.36 | 1904.03 | 2126.69 | 2129.36 | 2292.66 |
| Marine ecotoxicity (kg 1,4-DCB) | 2320.24 | 2503.5 | 2517.12 | 2255.52 | 2312.82 | 1911.55 | 2688.9 |
| Marine eutrophication (kg N eq) | 0.39 | 0.49 | 0.56 | 0.38 | −3.12 | 0.48 | 0.46 |
| Mineral resource scarcity (kg Cu eq) | 7.57 | 8.15 | 8.18 | 7.35 | 8.11 | 7.98 | 8.98 |
| Ozone formation, human health (kg NOx eq) | 206.98 | 223.5 | 224.83 | 195.51 | 222.13 | 218.23 | 239.05 |
| Ozone formation, terrestrial ecosystems (kg NOx eq) | 212.58 | 229.57 | 232 | 200.9 | 228.18 | 224.18 | 245.52 |
| Stratospheric ozone depletion (kg CFC11 eq) | 0.048 | 0.052 | 0.052 | 0.047 | 0.05 | 0.051 | 0.055 |
| Terrestrial acidification (kg $SO_2$ eq) | 158.17 | 170.6 | 171.5 | 151.23 | 169.33 | 167.83 | 183.03 |
| Terrestrial ecotoxicity (kg 1,4-DCB) | 837492.94 | 927768.5 | 928010.14 | 861497.66 | 927768.5 | 928010.14 | 993381.4 |
| Water consumption ($m^3$) | 54137.75 | 58452,13 | 58834.5 | 52566.74 | 58095.17 | 57529.13 | 63496.9 |

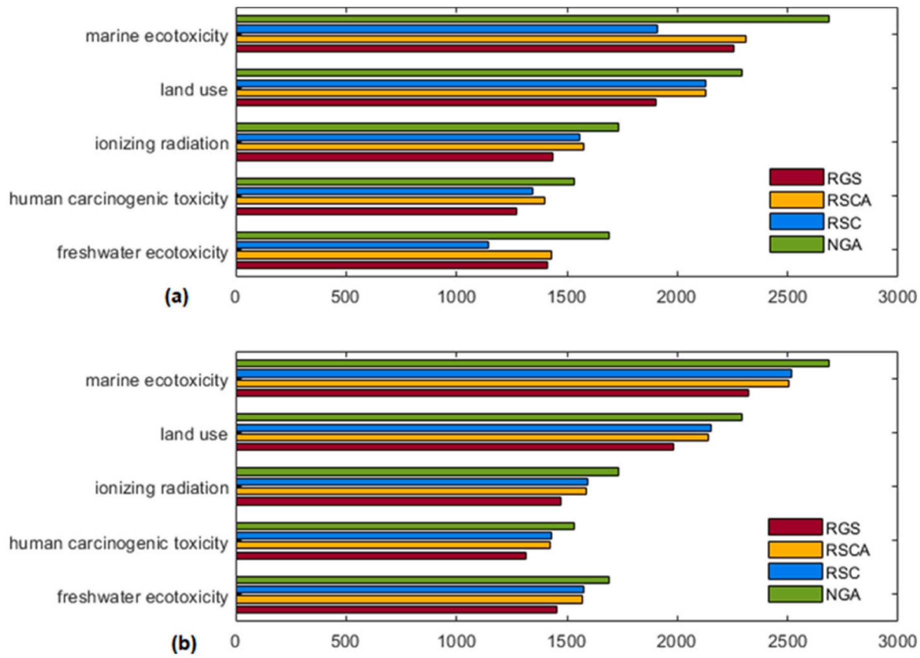


**Fig. 2.** Results of Recipe midpoint (H) method for five categories: human carcinogenic, freshwater and marine ecotoxicity, land use and ionizing radiation in (a) model 1 and (b) model 2.

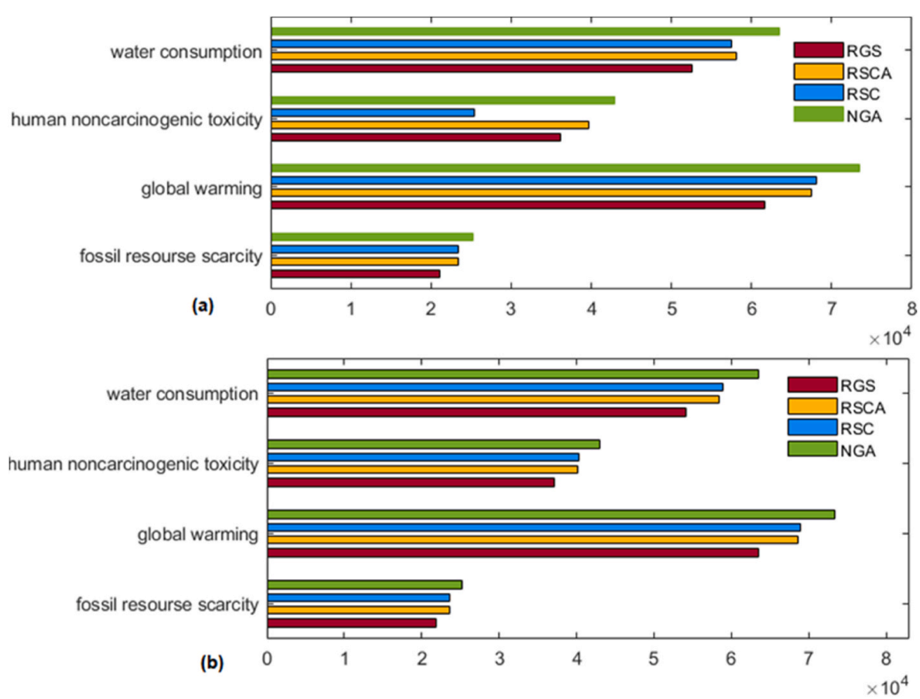


**Fig. 3.** Results of Recipe midpoint (H) method for five categories: human non-carcinogenic, water consumption, global warming and fossil fuel scarcity in(a) model 1 and (b) model 2.

A further step in the analysis focused the calculation of endpoint impact indicators, as presented in Fig. 5. In particular, in terms of global warming power (see Fig. 5(a)), there is no clear and strong separation between the cases in model 1 and in model 2. Between the recycled raw materials, the RGS turns out to have the least impact (around 60000 kg of carbon dioxide equivalent). Comparing this case to the one with natural raw material (NGA), in both models the GWP impacts are reduced of 13.4% and 16%, respectively. Instead, the RSCA case presents a reduction of equivalent $CO_2$ emissions of 8% in the first model and 6.55% in the second model. Analogously, the RSC cases consider decreasing emissions of 7.3% and 6% respectively, compared to the NGA case. Similar results and ratios between the four different cases characterize the other final impact categories, as visible in Fig. 5(b),(c),(d). In fact, the RGS case is characterized by a reduction of impact from 16.5% to 20.5% in terms of damage to human health, from 16.8% to 20.5% in terms of damage to ecosystem and then, from 15.3% to 19% in terms of damage to resource.

However, the scenarios with the use of RSC and RSCA show limited

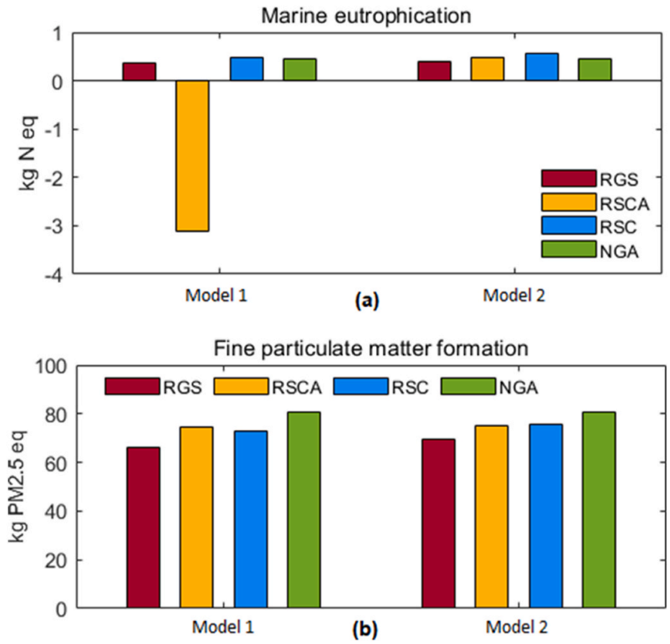


**Fig. 4.** Results of Recipe midpoint (H) method: (a) marine eutrophication, (b) fine particulate matter formation.

but visible differences compared to the NGA cases: the reduction of impacts is from 7% to 9% for RSCA and from 6.6% to 11.2% for RSC. Considering the obtained results, an in-depth analysis of the role of the individual processes in the specific impact categories, has been carried out in order to detect the most critical processes and phases. The analysis of the specific contribution of each process in the life cycle assessment of a paved surface implementation has allowed to define that transportation processes provides the main contribution in all the considered impact categories.

In fact, the transportation contribution is constantly equal or over the 99% of the total impact category. This underlines the significant role of the distance between the production site and the origin of the input material in the aggregates production. In general, the global warming impact of the processes could be consistently reduced by limiting the distances of transportation. Moreover, some negative impacts obtained in the processes contributions have been detected and are due to the fact that, in the model, the incoming waste has been modeled as avoided waste. These results confirm results of previous studies related to the recycling aggregates used in the cement production, such as in Tang et al. (2022). Moreover, similar results have been reported in Xiao et al. (2018) where the treatments of the raw materials have limited effects on the environmental impact of the whole construction process of a building. However, considering the strong importance of the transport phase of raw materials, a further sensitivity analysis have been conducted and described in the following. The contribution of transports in the environmental impact is consistent, and potential modifications would significantly affect the whole life cycle assessment results. Some literature articles have demonstrated that the transportation distance of coarse aggregates has a remarkable impact on the environmental benefits of recycled aggregates (Marinković et al., 2010; Xiao et al., 2018). In this work, only the distance of the incoming end of wastes of the recycled aggregates has been varied, keeping all parameters unchanged (Tang et al., 2022). The analysis has been conducted on the model 1 of the input materials, since represents the less conservative and

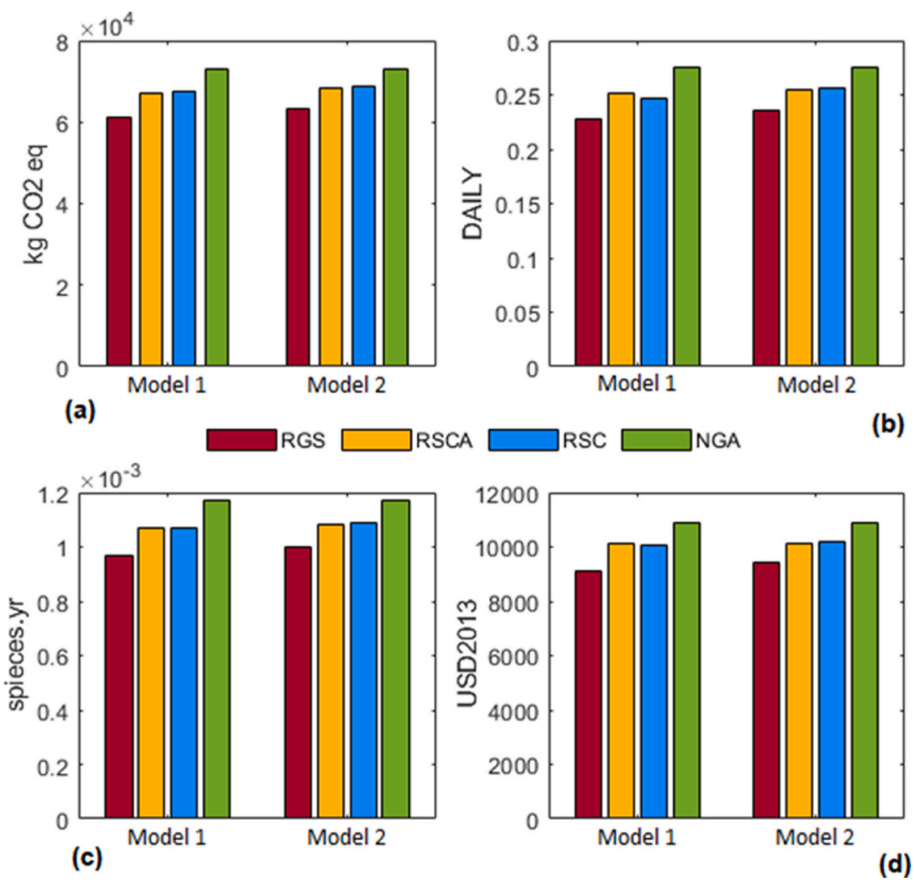


**Fig. 5.** Results of endpoint method: (a) IPCC 2013 GWP 100a and Recipe endpoint (H) categories, as (b) damage to ecosystems, (c) damage to human health and (d) damage to resource.

highest-impact situation for the recycled products. The variation of the GWP and Recipe endpoint categories have been reported in Fig. 6 as a function of the ratio between RA transportation distance and NA transportation distance.

It can be observed that an increase in this ratio led to a linear increase in the GWP and others indicators. The recycled materials keep lower impacts in all the categories until to an RA/NA ratio equal to 10. Then, the RGS material shows environmental impacts higher than virgin aggregates, starting from the GWP where RGS reaches the break-even point with NA at a ratio of about 12. The other two recycled materials are characterized by better results, reaching the break-even point around twenty times the distance of the virgin aggregates. In this study, the limits of the ratio, resulting from the sensitivity analysis, show higher values than the ones available in literature, but this is due to the characteristics of the materials. In fact, most of the results available in literature are related to recycled cement and mixture of recycled aggregates and cement; instead, in this case, the materials are only recycled products from end-of-wastes materials. These results show that the recycled materials, having the same mechanical properties of virgin aggregates, can be a solution for rural pavements with less environmental impacts, even if the materials come from long distance (within a radius of 300 km).

These results confirm previous studies where the use of recycled aggregates have demonstrated to reduce the environmental impacts of the construction process. Moreover, if the recycling process takes place at the same demolition site, the sustainability of the process increases, as demonstrated by Xiao et al. (2018). However, from the results, the paved surfaces in agricultural environment made by recycled materials, in different magnitude, show a reduction of the environmental impact, in all the indicators, if compared to the virgin aggregates materials. In particular, the paved surfaces made of recycled ground stone demonstrates to be the most sustainable. Moreover, in this particular case, the recycled aggregates have been used as single material for the construction and not blended with others, such as cement or bitumen. This aspect strengthens the fact that recycled materials, as standalone construction materials, can have a significant role in increasing the sustainability of farms for creation and maintenance of rural roads or yards.

## 4. Conclusions

A comparative LCA of four different aggregates, three recycled and one virgin, to be used for the realization of paved surfaces in agricultural context, has been carried out after a careful literature analysis and primary data collection. The availability of primary data about the recycling processes represents a significant aspect for the strength of the research carried out and the consequent results. The study identifies the scenarios to investigate, as well as to evaluate, the effective validity of the application of the circular economy concept in this sector. The results demonstrate that the use of recycled materials for a rural pavement construction could lead to a consistently lower impact for this type of groundwork. In fact, the whole recycled aggregates have a lot of leeway to be more sustainable than virgin natural aggregates, even if the end-of-waste materials come from demolition sites far from the production plant. As result of the study, the recycled aggregates, generally, have shown a visible reduction of the environmental impacts compared to the natural gravel aggregate, in all the models considered. Between the recycled products, considering the most sensitive impact categories such as climate change and damage to the environmental sectors, the recycled ground stone has the lowest environmental impacts.

A possible future extension of the study is to perform an overall assessment of the cost-effectiveness of the four different materials through a life cycle cost analysis. Further investigations, based on different and bigger geographical area, could give a wider and complete idea on the sustainability of the recycled inert materials, also considering the impact of the transportation detected in the study.

## CRediT authorship contribution statement

**Enrica Santolini:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, preparation, Writing – review & editing, Visualization. **Marco Bovo:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, preparation, Writing – review & editing, Visualization. **Alberto Barbaresi:** Conceptualization, Investigation, Writing – original draft, preparation, Writing – review & editing, Supervision. **Daniele Torreggiani:** Conceptualization, esources, Writing – review & editing, Project administration, Funding acquisition. **Patrizia Tassinari:** esources, Supervision, Project administration, Funding acquisition, All

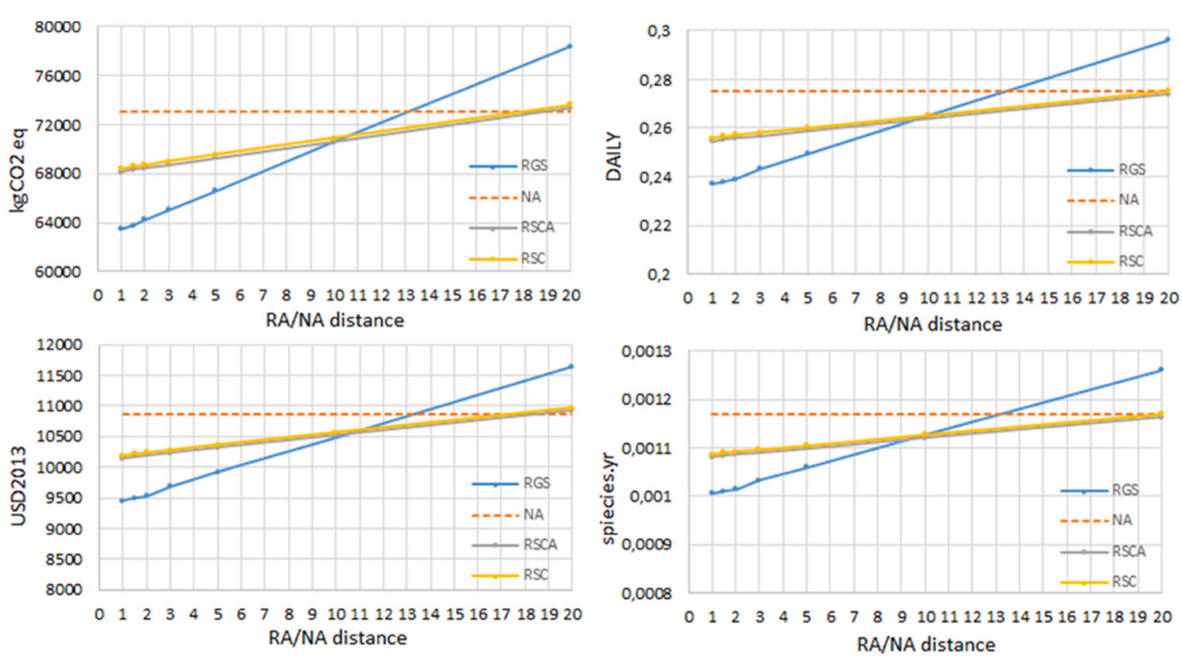


**Fig. 6.** Sensitivity analysis results of the GWP and ReCiPe endpoint categories, for the recycled aggregates.

authors have read and agreed to the published version of the manuscript.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data that has been used is confidential.

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