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Comparing bio-binders, rubberised asphalts, and traditional pavement technologies

Filippo Giammaria Praticò ^a, Giusi Perri ^b, Manuel De Rose ^b, Rosolino Vaiana ^b

^aDIIES Department, University “Mediterranea” of Reggio Calabria, Via Graziella - Feo di Vito - 89100 Reggio Calabria, Italy

^b Department of Civil Engineering, University of Calabria, Via P. Bucci - 87036 Rende, Italy

Corresponding author: giusi.perri@unical.it

Abstract

Nowadays pavement technologies must comply with sustainability requirements, including global warming, energy consumption, and quietness. On the one hand, global warming is the most important category of impacts analysed as it is primarily associated with climate change and with intrinsic effects on human health, weather, and natural habitats. The emission of greenhouse gases (GHGs), is essentially related to fuel combustion during construction and transportation operations, but also during the materials production processes. On the other hand, traffic noise is a major concern, being related to premature mortality and years lived with disability.

The road industry is focused on developing solutions able to face these issues and in the last years, the use of crumb rubber from end-of-life tyres and the use of binders combined with renewable natural resources (bio-binders) have gained momentum. Despite this, many uncertainties arise when comparing different solutions and this calls for specific comparisons in terms of life cycle assessment (LCA).

Based on the above, the objectives of the study described in this paper have been confined to i) comparing rubberized and bio-asphalts, and traditional pavement technologies from a broader perspective, including LCA-based criteria; ii) setting up a method to compare innovative (e.g. green) and traditional pavement technologies; iii) detecting, discussing, and promoting competitive equilibria among pavement technologies.

Six different alternative solutions were studied including two reference scenarios (traditional dense-graded and porous asphalt concrete), a solution with the use of crumb rubber, and a solution with a bio-binder.

Keywords

sustainable road construction; life cycle assessment (LCA); alternative materials; waste reuse; expected life; bio-asphalt; rubberised asphalt; noise impacts

1. Introduction

Recent European Union strategies pursue the goal of gradual reduction of Greenhouse Gases (GHG) emissions for 2030 to minimise climate change impacts. The latest regulations [1] set the target of climate neutrality in the Union by 2050 establishing the purpose of achieving zero emissions by that date. All sectors of the economy should contribute to climate action, including energy, industry, transport, waste, and land use. The long-term strategic objective is to achieve a climate-neutral economy with more cost-efficient resource use, improved energy efficiency, no net emissions of GHGs, and environment-related risks and impacts.

To this end, over the last years, the focus has shifted to the use of bio-materials in bituminous binders and mixtures (wood bio-oils, waste cooking oil, vegetable bio-oils, bio-oils of animal origin) [2–4]. Indeed, the dependence on petroleum-based products can be diminished by 100% replacement of bitumen (direct alternative binder, limited application mode), 25-75% replacement of bitumen (bitumen extender, common application mode), 0%-10% replacement of bitumen (bitumen modifier, the application mode is rather mature) [5,6].

The use of bio-binders with proper physical and chemical features to replace traditional petroleum-derived asphalt allows obtaining several benefits such as a reduction in the production temperature (compared to hot mix asphalt mixtures, HMA), a reduction in energy input and paving costs (about 20%), and a decrease in GHG emissions up to 30% [7,8].

Tokede et al. [9] reported a 5.72% reduction in global warming potential (GWP) by replacing a percentage of bitumen (about 25%) with lignin in asphalt production. In their study, Samieadel et al. [10] compared the traditional asphalt binder with a bio-modified binder produced by mixing asphalt binder with bio-binder obtained from swine manure; the purpose of their research was to assess both processes in terms of energy consumption and environmental performance. LCA results showed an improvement for the bio-binder strictly related to the lower energy required to ensure the proper workability of asphalt (the reduction is over 50%). Furthermore, the production of conventional asphalt binder is characterised by CO₂ emissions that are five times higher than those of the bio-binder production process. A comparison with traditional asphalts highlighted the most significant advantages associated with bio-asphalts such as lower emissions and energy consumption during the production and application stages [11].

Mantalovas et al. [12] performed an LCA to discuss the impactful factors of three different asphalt pavements including a bio-asphalt mixture incorporating a bio-based binder with the function of replacing virgin bitumen. The authors concluded that the bio-asphalt contributed to reducing the global warming potential indicator.

In some cases, products and processes do not meet adequate criteria from a sustainable perspective and their implementation may not be considered beneficial to the environmental system. For this reason, the environmental impacts of specific materials should be investigated in each situation in order to analyse the adequate use of waste materials, the potential decrease in the demand for imported petroleum, and the achievement of sustainability and circular economy criteria.

Another important issue refers to the consideration of the durability coupled with the LCA [13,14]. Indeed, the current research on the benefits of using alternative binders in terms of service life is lacking, does not cover all bio-solutions, and should analyse both durability-related performance and environmental impacts synergistically. The reduction of service life is significantly affected by the ageing of the asphalt binder. For example, some bio-asphalt binders are more susceptible to oxidative and thermal ageing with a direct effect on the performance of the mixture [15–17]. However, some experimental applications demonstrated good anti-ageing properties of bio-asphalt; for example, Chebil et al. [3,18] observed that biochar can reduce the oxidation process.

Some bio-asphalts exhibit low moisture resistance with consequences on the properties of the mixture such as adhesion and cohesion [17], whereas other test results show that the water stability of the bio-asphalt is better than that of traditional asphalt mixture [3].

Compared with traditional petroleum mixtures, bio-asphalt mixtures have lower high-temperature stability and higher crack resistance at low temperatures [3]. Zhang et al. observed that bio-binders obtained using waste oil and refined waste oil improved asphalt performance at low temperatures [3,19]. Mohammad et al. [20] investigated asphalt mixtures with different percentages of bio-binder and draw the conclusion that the presence of bio-binder improved the low-temperature fracture performance; in addition, they observed a lower fracture resistance for the bio-binder mixture when compared with traditional mixes. This last result was associated with the stiffening effect of the bio-binder on the mix. Djumari et al. [21] reported an improvement in the stability of asphalt mixtures produced using resin-modified bitumen.

Generally, bio-binders are linked to performance issues in terms of ageing resistance and high-temperature behaviour. Several authors report a reduction in the softening point, compared with virgin asphalts. Wang et al. [22] reported a softening point of 46.5 °C for bio-asphalt (15% bio-binder content, derived from rice husk, wheat straw, etc) [23,24]. He et al. [25] observed a softening point of 56-60 °C for a modified bio-asphalt, Gao et al. [26] found that the softening point was in the range of 49-51 °C for a bio-asphalt modified with Styrene-Butadiene-Styrene (SBS). Furthermore, bio binders often undergo an increase in penetration and ductility and this condition is strictly affected by the low viscosity and the high fluidity of the binder [3]. A review of previous studies reports that for some types of bio-asphalt (derived from sawdust, waste oil, cottonseed and soybean waste) the penetration and the ductility increase when the percentage of bio-binder also increases, whereas the softening point is approximately comparable [3]. The addition of waste vegetable oil resulted in increased penetration, ductility, and susceptibility to high temperatures (decrease in asphalt resistance to

rutting) [27,28]. In summary, a review by Yuniarti et al. [28] points out that the effects of bio-binder are correlated with an increase in penetration and ductility and a decrease in the softening point, regardless of the bio-binder used (with waste cooking or vegetable oil, pine resin and gum rosin).

The importance of the issues and perspectives above is going to gain momentum because paved surfaces cover a high percentage of our cities' surfaces (e.g., 30%, cf. [29]). Furthermore, the majority of these surfaces are asphalt concretes (e.g., 94%, cf. Bucher, [30]). From a LCA perspective, this explains how much important is to improve the sustainability and the performance of pavements and to assess the best pavement technology through comparisons and analyses [31].

To this end, it is noted that two crucial aspects are often disregarded, i.e., the availability of the reused/recycled resources and, as mentioned above, the expected life of the products (i.e., friction courses) set up. In other terms, this also refers to the assessment of the actual amount per year of the given waste material (e.g., plastics) and the corresponding actual amount needed for the specific product (e.g., HMA with plastics).

Additionally, for the expected life, note that this issue is linked to the tendency to develop reference ranges based on a product family approach, because of the possibility to group different products that have a common set of traits, having "product families for LCA comparison" (cf. [32]). To this end, for the expected life of the bituminous materials produced using bio-asphalts, from an experimental standpoint, it is possible to observe what follows:

- Usually, the penetration of bio-asphalts (i.e., bio-binder plus asphalt binder) is higher than the corresponding value for the asphalt binder [3].
- Furthermore, the bio-asphalt-based HMAs have a certain probability to undergo failures due to high-temperature stability and water-related stability).
- Furthermore, from a predictive standpoint, the same average properties of bio-binders imply lower moduli and lower fatigue life. Indeed, in the first approximation, the number of repetitions to failure decreases for higher tensile strains and these latter correspond to lower moduli (cf. [33–35]).
- All these facts imply that there is a quite high probability that their expected life is lower than the one of a traditional HMA.

The use of alternative materials, wastes from everyday life, renewable materials, industries, and agricultural and forestry by-products is attracting growing attention in order to reduce carbon footprint. The comparison with traditional materials and means of construction is essential, given the fact that these alternatives could help in the reduction of emission generation and the consumption of natural non-renewable resources such as aggregates or bitumen [36–40]. Among different sustainable pavement materials, crumb rubber from end-of-life tires is the most commonly investigated in the field of flexible pavement construction [41,42]. For example, Chiu et al. [43] compared the environmental loads of rehabilitating one lane-kilometre of asphalt pavement using traditional HMA and three recycled materials, including asphalt rubber. In this study, the use of asphalt rubber is associated with a reduction in eco-burden by 23%, given the longest service life of this option when compared to traditional HMAs. Zanetti et al. [44] reported lower environmental impacts and contaminants in the asphalt fumes of mixtures with crumb rubber. However, increasing the percentage of crumb rubber in the mix can be associated with higher energy consumption but lower GWP [45,46].

Puccini et al. [47] reported a 50% decrease in environmental burdens associated with the use of warm mix asphalt containing crumb rubber and reclaimed asphalt pavement (RAP) for wearing course. Gamboa et al. [48] concluded that environmental damage could be reduced by 48% by implementing rubberized asphalt (where the crumb rubber is added through the dry method) instead of the conventional alternative.

The LCA performance of both bio-binders and rubberised is affected by paving technologies and/or by the use of other concurring recycled materials.

For paving technologies, the focus is on warm mix asphalts which result in lower energy consumption and pollutant emissions, compared to traditional HMA-related processes [41]. The reduction of the amount of asphalt and heat consumption are the key factors contributing to a lower environmental load [43]. In pavement construction, energy and environmental impacts are strictly related to the production process. According to

Siverio Lima et al. [49], this phase is responsible for 78% and 55% of the impacts in terms of non-renewable cumulative energy demand and global warming potential, respectively.

The use of recycled materials, such as RAP, requires less consumption of virgin bitumen and aggregates [41,50]. Compared to conventional mixtures, higher percentages of RAP involve the mitigation of negative environmental impacts [49,51]. When high percentages are considered, also the inclusion of crumb rubber in the mixture allows smaller amounts of aggregates [52]. The impact on resources is estimated to be 43% higher for conventional asphalt when compared with rubberized asphalt [48].

The use of eco-friendly materials is encouraged for two main reasons: i) these materials may allow the partial replacement of virgin materials (depletion of resources); ii) new asphalt mixtures less dependent on petroleum-based products may contribute to reducing environmental burdens in the life cycle as the asphalt binder is the most energy-consuming process [51]. In several LCA applications, asphalt production in the plant is the primary contributing factor to the increase in both fuel and electricity consumption [53]; this condition is mainly due to the high temperatures required for most of the process subphases, such as for drying aggregates, the melting of bitumen and additives, the mixing and storage of asphalt mixtures [54].

Table 1 illustrates examples of GWP and global energy requirement (GER) for HMAs. Global warming is the most important category of impacts analysed as it is primarily associated with climate change and with intrinsic effects on human health, weather, and natural habitats [55]. The emission of GHGs is essentially related to fuel combustion during construction and transportation operations, but also during the materials production processes.

Table 1. Carbon footprint and energy consumption for HMA.

Note	GWP	GER	Reference
Bituminous concrete (binders, aggregates, manufacture, transport, laying)	0.054 kg CO ₂ -eq/kg	0.68 MJ/kg	[56,57]
HMA (10 cm, 2240 kg/m ³) (raw materials, heating, mixing, transport, placement, and compaction)	13.1 kg CO ₂ -eq /m ²	198.5 MJ/m ²	[57]
Porous asphalt concrete (production, transport, construction)	12.87 kg CO ₂ -eq /m ²	-	[52]
HMA (16 cm) (Production, transport, construction)	14.6 kg CO ₂ -eq /m ²	-	[58]
HMA (4 cm, 2300 kg/m ³) (Laydown, hauling, production, aggregate and binder production)	-	55.2 MJ/m ²	[59]
HMA (4 cm, 2300 kg/m ³) (Laydown, hauling, production, aggregate and binder production)	-	62.56 MJ/m ²	[59]

Finally, it is noted that the following issues arise when dealing with bituminous mixtures for friction courses:

- Many impacts and indicators derive from the processes that each material undergoes during its life cycle. Is it consistent to consider these impacts as different impacts or, on the contrary, are they basically the same impact? Is there a so-called multi-collinearity issue (i.e., where GWP and GER are not independent variables and are correlated)? In the case of non-proportionality between GWP and GER, what could be the main causes (e.g., different energy sources or/and non-GHG emissions)?

- When setting up a method to compare different alternatives that imply the reuse or recycling of waste materials with the aim of improving the sustainability and the quietness of pavement technologies, should other supplementary impacts (e.g., acoustic impact and diversion of waste from landfill) be considered? For example, the use of crumb rubber implies the reduction of the waste volume due to old tyres. Furthermore, these volumes depend also on the same expected life, because higher expected lives result in lower volumes, the remaining factors being constant.
- If competing pavement technologies have different expected lives is it possible to neglect this diversity when comparing the impacts during their life cycle? Is it possible to disregard that the life cycles of the competing alternatives are very different and consequently their impacts referred to a common baseline are biased if their expected life is not considered [60,61]? This issue is quite difficult to solve, due to the uncertainties that refer to the derivation of the expected life of a friction course, where there is a sort of superposition of many characteristics to fulfil (e.g., friction, surface texture, and mechanistic performance) [62].

1.1 Goal and scope definition-objectives

Based on the above, the objectives of this paper were confined to:

- 1) comparing rubberized, bio-asphalts, and traditional pavement technologies from a broader perspective, including LCA-based criteria;
- 2) setting up a method to compare innovative (e.g. green) and traditional pavement technologies;
- 3) detecting, discussing, and promoting competitive equilibria among pavement technologies.

Innovative and traditional pavement technologies were considered. In particular, the alternatives include the use of crumb rubber (dry method) and a solution involving 100% replacement of bitumen (bio-binder produced by mixing different materials including wastes such as waste olive oil and crumb rubber from end-of-life tires - wet method).

2. Tasks and methodology

Based on the issues above, the overall methodology has been set up and developed as follows:

Task 1: Goal and scope definition. Selection of scenarios. Selection of the functional unit.

Task 2: Tests and Inventory.

Task 3: Derivation of pollution indicators and impacts.

Task 4: Derivation of scenarios' durability and subsequent normalisation of impacts.

Task 5: Analysis of the results and conclusions

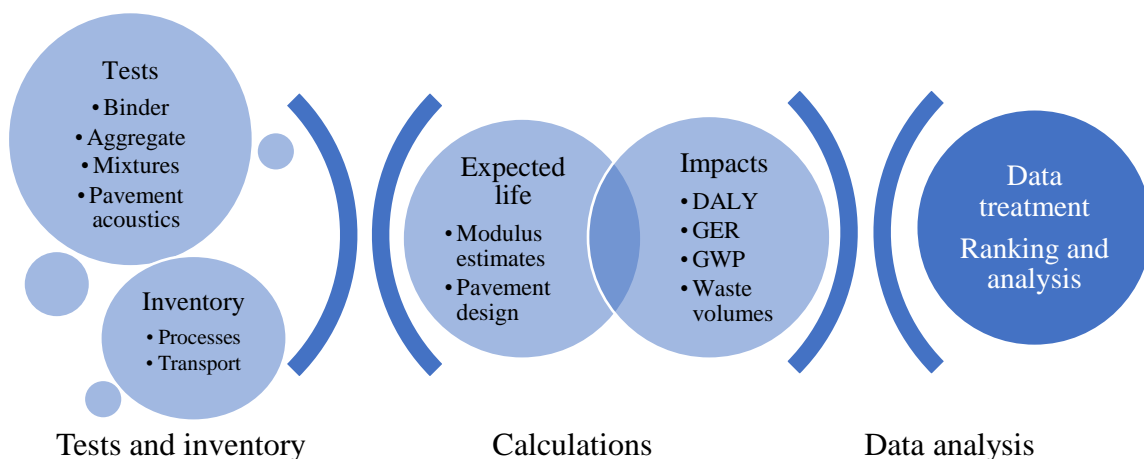


Figure 1. Methodology

2.1 Impact Assessment

2.2 Pavement technologies

The functional unit used in this study is 1 m² of road pavement. This reference unit is chosen for comparison purposes among the selected pavement solutions and with the literature.

The analysis follows the “cradle-to-grave” approach, assuming that system boundaries include all the activities related to raw materials acquisition and composite materials production, construction and transportation operations, and end-of-life (EoL) stage processes (milling and disposal of the milled material). In detail, impact contributions can be associated with four main life cycle phases: i) production, ii) construction, iii) transportation, and iv) end of life; these stages can be split into sub-processes depending upon the considered pavement alternative.

Significant differences between the analysed solutions relate to the input materials and resources thus production is the phase that requires a deeper investigation.

The study is extended to a road 150 m long section and 3.75 m wide with a total pavement thickness of 34 cm. Pavement thickness was assumed to be the same for the different scenarios in order to simplify the comparison process. The pavement structure, which is placed on the subgrade, is composed of a friction course (4 cm) and a granular base course (30 cm). The friction course is the main variable in all three investigated alternatives. The variation in the friction layer allows defining the following scenarios:

- REF_DG: (reference scenario) the friction course is a dense-graded asphalt concrete. Asphalt mixture includes modified bitumen by SBS polymer, hydrated lime (cf. [63]), calcareous filler, and mineral aggregates (23.5% fine aggregate and 68.5% coarse aggregate);
- REF_PA: (reference scenario) the friction course is porous asphalt concrete. Asphalt mixture includes: modified bitumen by SBS and cellulose fibres used to mitigate binder drainage, hydrated lime, calcareous filler, and mineral aggregates (6% fine aggregate and 88% coarse aggregate);
- L_DG*_CR: the friction course asphalt mixture includes modified bitumen by SBS, hydrated lime, calcareous filler, and mineral aggregates (48% fine aggregate and 42% coarse aggregate), crumb rubber (CR, type RARX, 1.9% by mix weight) added to the mixture by dry method. This scenario refers to the project LIFE E-VIA and to a low nominal maximum aggregate size grading (low NMAS, DG*);
- L_DG*: where the same aggregate grading, hydrated lime, and bitumen weight as *per* Scenario_1 was used but no crumb rubber was included in the mix;
- B-B_DG: the friction layer is composed of a mixture of aggregates (the same as per Scenario_0), hydrated lime, and bio-binder obtained by mixing colophony rosin, crumb rubber (wet method), paraffinic wax, SBS, and waste olive oil (no longer suitable for human consumption). Bio-binder production refers to the project PRIN 2017 | USR342.
- B-B_PA: bio-binder mixture where the same aggregate grading as per Scenario_0* was used.

By referring to the differences between the dry method (rubberized asphalt, cf. scenario L_DG*_CR) and the wet method (cf. scenarios B-B_DG and B-B_PA), these were considered in terms of both pre-processing (different size) and processing (mixing vs. modifying).

The unbound base layer is common to all the scenarios and it includes a given gradation of mineral aggregates (60% coarse aggregate, 30% fine aggregate, and 10% calcareous filler), compacted at a given moisture content (11% water by aggregates weight).

Subgrades, embankments, drainages, and road markings are not included in the analysis.

Table 2 summarises the scenarios investigated in the study.

Table 2. Summary of the analysed scenarios.

Scenarios	REF_DG	L_DG*_CR	B-B_DG	REF_PA	L_DG*	B-B_PA
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Friction course	Mix type	Dense-graded	Dense-graded	Dense-graded	Porous asphalt	Dense-graded	Porous asphalt
	Binder type	Modified bitumen (MB)	Rubberized asphalt	Bio-binder	Modified bitumen (MB)	Modified bitumen (MB)	Bio-binder
	Aggregate type	A	A+CR	A	A	A	A
	Aggregate gradation	DG16	DG8	DG16	PA	DG8	PA
Base course		unbound base course					

Symbols

DG: dense-graded asphalt; A: mineral aggregates; CR: crumb rubber (type RARX); B-B: bio-binder; PA: porous asphalt concrete; MB: modified bitumen by SBS polymer;

DG: gradation for DGs (8% mineral powder, 23.5% fine aggregate, 68.5% coarse aggregate);

DG*: 10% mineral powder, 48% fine aggregate, 42% coarse aggregate;

gradation for PAs (6% mineral powder, 6% fine aggregate, 88% coarse aggregate);

where: mineral powder <0.075 mm (1% by aggregate weight of mineral powder is hydrated lime), fine aggregate 0.075/2 mm, and coarse aggregate 2mm/15mm

2.3 Tests and inventory

Table 3 and **Figure 2** refer to the main tests carried out in this study, while **Tables 4 to 8** refer to the inventory of the impacts for production, transportation, construction and end of life.

While **Table 3** clarifies how the tests carried out refer to the impacts, from **Figure 2** the differences among the solutions emerge, where the composition of the bio-binder (without bitumen) leads to higher penetrations and higher softening points.

Table 3. Main tests carried out. (CPX: Noise measurements according to the Close ProXimity method; $L_{eq,D,0}$ and $L_{eq,N,0}$ are the day (D) and night (N) equivalent sound pressure levels of the pavement surface, information on the year of noise monitoring since construction is reported too (in this case 0 stands for the construction year).

Material	Main tests carried out (*) (**)			Methodology	Main impact addressed
Bio-binder	Penetration= 84 dmm	Softening Point= 93.8 °C		Modulus estimate and Empirical-mechanistic design [64]	Expected life
Modified bitumen	Penetration= 54 dmm	Softening Point= 51.2 °C			Expected life
Aggregate	Gradation (see Figure 2)				Expected life
Pavement	CPX (see Figure 2) (**)	$L_{eq,D,0}$ (see Figure 2)	$L_{eq,N,0}$ (see Figure 2)	See standards below	DALY (Disability-adjusted life year)
(*) Standards: Penetration (EN 1426), Softening Point (EN 1427), aggregate gradation (EN 933-1), CPX (ISO 11819-2)					
(**) cf. https://life-evia.eu/ ; https://www.lifesneak.eu/					

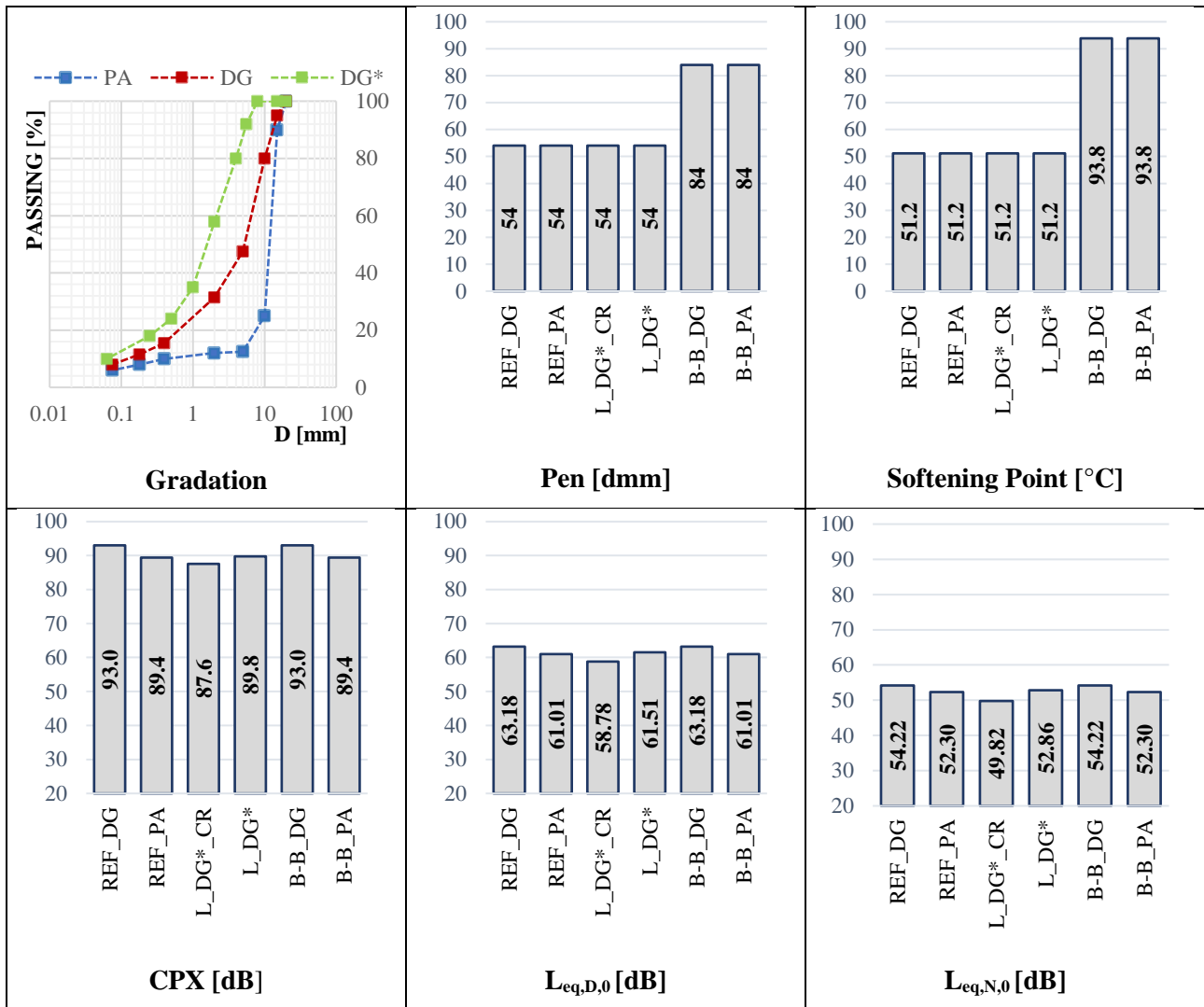


Figure 2. Main results of the tests carried out.

The inventory is based on the systematic definition of the inputs and outputs of the system allowing a quantitative assessment of materials, energy consumption, and air emissions from an environmental point of view [65]. To accomplish this activity, information concerning each selected impact must be acquired for each process involved in the system from cradle to grave. Data are collected from the literature, publicly available databases, manuals, and manufactory specifications. Further details on the data collection can be found in the following subsections. The corresponding amounts per functional unit are derived.

For the production of input materials data on bitumen manufacturing are acquired from Eurobitume [66], which reports the life cycle inventory for the production of 1 tonne of bitumen. Information includes the environmental impacts of the following subphases: crude oil extraction, transport to Europe (pipeline and ship transport), manufacturing of bitumen in the refinery, and hot storage of the final product.

Table 4 lists data for each production process confined to emissions to air and energy consumption. Furthermore, Table 4 reports the data source for each input material process associated with the investigated scenario.

Table 4. Average air emissions and energy consumption for each production process.

Scenarios	Process	Emissions [kg CO ₂ -eq/t]	Energy consumption [MJ/t]	Reference
REF_DG REF_PA L_DG*_CR L_DG*	Bitumen production	189.12	510.00	[66]
All	Coarse aggregate production	3.37	16.60	[67,68]
	Fine aggregate production	5.89	22.62	[68]
	Calcareous filler production	7.36	28.00	[68]
	Asphalt mixture production	26.24	363.24	[69]
	SBS production and transport	3,715.54	73,042.86	[66]
	Hydrated lime production	1,260.00	3,000.00	[70]
REF_PA	Cellulose fibres extraction and processing	880.00	70.00	[71]
L_DG*_CR	Crumb rubber (type RARX) production	206.04	9,236.65	[72]
	Crumb rubber production	345.00	1,822.63	[73]
B-B_DG B-B_PA	Colophony rosin production	1,680.00	19,000.00	[74]
	Olive oil production	600.00	37,663.76	[75,76]
	Paraffinic wax production	609.00	510.00	[77]

For bio-binder production (by a mixer powered by electricity) an energy consumption of 72.00 MJ/t bio-binder was assumed [66].

Furthermore, the energy consumption needed to produce tires was not considered. Indeed, used tires were taken into account. For the biomasses, in Table 4 it is specified that acquisition and processing were considered (for example, see “Olive oil production”, cf. Table 4: indeed, this oil was supposed to be inedible (after “used by” date), but it underwent as usual the production cycle).

Data on emission generation related to the production of rubber asphalt (L_DG*_CR) were assumed to be the same obtained for the traditional asphalt mixture as literature shows that values are similar [78,79]. Moreover, the addition of crumb rubber by the dry process does not increase the energy consumption during mixing [80]. For B-B_DG and B-B_PA it was assumed that emissions and energy use were similar to those assessed for the HMA plant operation process [69].

The ISO standard [81] requires LCAs to include the feedstock energy for relevant inputs of raw materials which are not used as sources of energy in the modelled process system, such as asphalt binder, which is used as a material rather than as fuel [55]. However, the inclusion of feedstock energy in LCA studies is recommended for cradle-to-grave studies and not necessarily for cradle-to-gate investigations [82]. In this study, the feedstock energy of bitumen was assessed according to ISO standards and it was considered separately from the process energy used within the system [82].

For GHG emissions during transportation and construction activities the environmental impacts are strictly related to the combustion-related emissions from vehicle and equipment usage. GHG emissions of the specific vehicle “v” were assessed by multiplying the fuel needed (FC) for each task (j) by the corresponding emission factor (EF), according to the general equation:

$$\text{Emission}_{ij} = FC_{vj} \cdot EF_i \quad \text{Equation 1}$$

where the subscript “*i*” refers to each air pollutant: carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄).

The emission factor for diesel was assumed to be 2.60 kg of CO₂ per litre [83]. **Table 5** summarizes the emission factors for N₂O and CH₄, depending on the vehicle type.

Table 5. Emission Factors for on-road and off-road diesel vehicles considered in the study [84].

Vehicle Class	Vehicles/Equipment used in the study	CH ₄	N ₂ O
		kg/l	kg/l
Construction/Mining Equipment	Paver, Vibratory roller, Motor grader, Milling machine, Truck (32 t)	2.48E-04	2.30E-04
Industrial/Commercial Equipment	Tanker truck,	2.46E-04	2.30E-04
		kg/km	kg/km
Light-Duty Trucks	Small lorry (3.3 t)	1.80E-05	1.33E-05

For transportation activities, **Table 6** lists all the transportation processes comprised in the study system and the vehicles used in each activity. These activities include the transportation of input materials from the source to the mixing plant (such as bitumen, waste olive oil, aggregates, crumb rubber, colophony rosin, and paraffinic wax) and the transportation of manufactured mixtures close to the paver in the construction site (the mixing plant-construction site distance is 25 km).

Table 6. Processes and vehicles used in the considered transportation activities.

Scenario	Process	Vehicles/Equipment type
REF_DG REF_PA L_DG*_CR L_DG*	Transport of bitumen from the refinery to the mixing plant	Tanker truck (11,924 l [85])
B-B_DG B-B_PA	Transport of waste olive oil to the mixing plant	
L_DG*_CR	Transport of crumb rubber (type RARX) to the mixing plant	
B-B_DG B-B_PA	Transport of colophony rosin to the mixing plant	Small lorry (3.3 t)
B-B_DG B-B_PA	Transport of crumb rubber to the mixing plant	
B-B_DG B-B_PA	Transport of paraffinic wax to the mixing plant	
All	Transport of aggregates from the quarry to the mixing plant Transport of manufactured materials from the production site to the construction site Transport of milled material to landfills	Truck (32 t)

The fuel consumption assessment is different for each process and type of vehicle, depending on the available information. The fuel consumed by the tanker trucks was obtained considering the total number of trips

required to complete the specific transportation activity and including empty returns. The number of trips was calculated based on the volume to be moved and the capacity of the tanker truck (11,924 l/tank [85]). The fuel consumption of the tanker truck per km is assumed to be 0.42 l [85]. Air emissions associated with the transportation activities of the selected small lorry were calculated by taking into account data available in the European Reference Life Cycle Database (ELCD) [67]. In particular, CO₂ emissions [kg] depend on the distance travelled in kilometres and the mass transported by the lorry expressed in tonnes. CH₄ [kg] and N₂O [kg] emissions were evaluated as a function of the distance covered [km] and the corresponding emission factors values stated by EPA [84] for light trucks (**Table 5**).

For the 32 t selected truck, fuel consumption was calculated using the following equation [86,87]:

$$FC_{\text{truck}} [l/m^3] = \frac{K [-] \cdot d [km] \cdot I_c [l/km]}{C [m^3]} \quad \text{Equation 2}$$

where K is a coefficient taking into account the different fuel consumption between a fully loaded truck and an empty one (K=1.7), d is the average distance covered during the specific activity, C is the capacity of the truck (22 m³), and I_c is the fuel consumption at maximum load. Concerning the evaluation of this last parameter, a linear relationship was assumed between I_c and the truckload in order to consider the different maximum loads depending on the type of transported material. The relationship was defined based on the values found in the literature for the type of truck considered [88]. In light of the above, it was assumed that I_c was 0.44 and 0.41 for the transportation of aggregates and the asphalt mixture, respectively [89].

Table 7 reports the transport distances for each material used in the study. Also, each quantity of material to be transported is reported in the table. It is worth noting that the same distance (80 km) was selected for transporting hydrated lime, SBS, crumb rubber, and bio-binder components to the mixing plant. The assumption of considering a fixed transportation distance (e.g., the distance between the storage centre and the mixing plant) allows for a more significant comparative analysis between the scenarios, as emissions generated during transportation activities are affected by the distance covered and the mode of transport.

Table 7. Average transportation distances and quantities needed for each material used.

Materials	Quantity [kg/FU]						Transportation Distance [km]
	Scenarios						
	REF_DG	REF_PA	L_DG*_CR	L_DG*	B-B_DG	B-B_PA	
Mineral aggregates							
<i>Coarse aggregate</i>	64.10	72.09	36.90	37.87	60.13	64.38	40
<i>Fine aggregate</i>	21.99	4.91	42.17	43.28	20.63	4.39	
<i>Calcareous filler</i>	6.55	4.10	7.91	8.11	6.14	3.66	
Bitumen	4.97	4.80	5.53	5.56	-	-	60
Hydrated lime	0.94	0.82	0.88	0.90	0.88	0.73	80
SBS	0.25	0.24	0.28	0.28	0.19	0.16	80
Cellulose Fibres	-	0.24	-	-	-	-	80
Crumb rubber (type RARX)	-	-	1.81	-	-	-	80
Colophony rosin	-	-	-	-	2.44	2.03	80
Waste olive oil	-	-	-	-	0.85	0.71	80
Crumb rubber	-	-	-	-	0.80	0.66	80
Paraffinic wax	-	-	-	-	0.53	0.44	80

In the assessment of energy consumption during transportation activities, the energy required to maintain the bitumen temperature within the storage tank was also taken into account. More specifically, a contribution of 70.1 MJ/t was considered [66].

For the construction stage and EoL phase, note that fuel consumption is related to different types of equipment used in laying and compaction operations. Information on construction equipment, such as the main specifications and fuel consumption of each machine, is reported in **Table 8**. The equipment data were collected from the manufacturer’s specifications, available free databases, and previous studies [90].

Table 8. Construction site equipment and main specifications.

Scenarios	Life cycle stage	Construction site equipment	Producer/model	Fuel consumption [l/h]	Average operating width [m]	Average working speed [km/h]
All	Construction	Paver	Bomag BF 600	43.1	2.5	1.3
		Vibratory roller	Bomag BW 203 ad-4	37.6	2.1	3.0
	EoL	Motor grader	CAT 12M2	40.0	3.7	23.0
		Milling machine	Wirtgen 220 Fi	60.0	2.2	2.64

The total fuel consumed in each activity was assessed as a function of the following parameters:

- the total operating time required to complete each task (laying and compaction for the construction and milling for the disposal of the friction course);
- the specific equipment productivity that depends on the machine specifications such as the average working speed, the operating width, and the number of machine passes (e.g., the number of roller passes to achieve the desired compaction level).

The GHG emissions for construction activities are evaluated using Equation 1 and the emission factors for the “construction/mining equipment” class of vehicles are listed in **Table 5**.

The end-of-life phase includes two main activities: the milling of the surface pavement layer and the transportation of the milled material to the landfill (the average transportation distance worksite-landfill was 100 km).

2.4 Derivation of the impacts

The main impact categories assessed in this study are:

- Global warming potential (GWP) for the production, construction, transportation, and end-of-life stages;
- Global energy requirement (GER) for the production, construction, transportation, and end-of-life stages;
- Disability-adjusted life year (DALY) for the operations stage;
- Volume of waste generated (end-of-life).

2.4.1 GWP and GER

These indexes were evaluated at the midpoint level from resource consumption flows (energy, natural resources) and emissions to air (climate change on a 100-year horizon) [65].

GWP is a measure of the effects of different gases that remain in the atmosphere over a chosen time horizon. The Kyoto Protocol is based on GWPs for a period of 100 years from emission. The selected GHGs are carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄). These gases are considered contributors to GHG emissions by the Intergovernmental Panel on Climate Change [36]. Carbon dioxide equivalents (CO₂-eq) is the standard reference unit for the comparison of different GHG emissions [91]. Gas emissions were converted to CO₂ equivalents by multiplying their global warming potential reported by the EPA [84]. In particular, CO₂ has a GWP of 1 because its concentration in the atmosphere lasts more than 100 years; the GWP of methane

is assumed to be 25 for a 100-year timescale; N₂O is estimated to have a GWP of 298 over 100 years. This process allows for a better understanding of the magnitude of potential impacts by translating environmental flows into environmental impacts [55].

Furthermore, the different alternatives are compared in terms of energy consumption, allowing for quantifying the direct and indirect energy use over the investigated life cycle phases.

2.4.2 DALY

This study addresses human health impacts in terms of annoyance and sleep disturbance due to acoustic impact of traffic during operations. Vehicles noise is not a negligible issue in urban centres and can significantly affect the quality of life of people living in the closest areas to the road [92,93]. The reference unit used in the quantitative assessment of the acoustic impact on human beings is the DALYs (disability-adjusted life years). The use of DALY is recommended by the World Health Organization (WHO) and refers to the loss of the equivalent of one year of full health [94]. Data on traffic noise emissions (cf. **Figure 2**) allowed assessing the equivalent sound pressure levels for the day-time (6.00 AM – 22:00 PM) and night-time (22:00 PM – 6:00 AM), $L_{eq,D}$ and $L_{eq,N}$, respectively. The number of potential impacted people was assessed taking into account the buildings close to the case study road (9 buildings) and the population density which was assumed to be three persons per household. The number of people with high annoyance (HA_x) and high sleep disturbance (HSD_x) in the service year X was obtained by the following relationships [95]:

$$HA_x = \sum_{j=1}^9 \frac{P(j)}{1 + \exp(-(-8.4495 + 0.1115 \cdot L_{eq,D,X}(j)))} \quad \text{Equation 3}$$

$$HSD_x = \sum_{j=1}^9 \frac{P(j)}{1 + \exp(-(-7.1315 + 0.0976 \cdot L_{eq,N,X}(j)))} \quad \text{Equation 4}$$

where $L_{eq,D,X}$ and $L_{eq,N,X}$ are the sound pressure levels related to day-time and night-time, respectively, P(j) is the total number of people in the household “j”.

The human health impacts (HI) of noise, expressed in DALY, were calculated as follows:

$$HI_x = HA_x \cdot DW_{HA} + HSD_x \cdot DW_{HSD} \quad \text{Equation 5}$$

where DW_{HA} and DW_{HSD} are the disability weights assumed to be 0.02 and 0.07, respectively [95]. Equations 3-5 allow quantifying the human health impacts of noise for the X-th year of pavement service time (with $X=0 \dots N$) where N is the expected life and 0 refers to the construction time. The values of $L_{eq,D,0}$ and $L_{eq,N,0}$ (construction year) were obtained by traffic noise monitoring (see Figure 2). The assessment of DALY over time requires some hypothesis on the acoustic aging of the asphalt pavements. To this end, it is noted that recent studies report an increase of about 0.5 dB per year for CR-added mixes, an increase of about 1 dB per year for DG mixes, and 0.9 dB per year for porous graded asphalt pavements at city streets and with low traffic speed [96,97].

2.4.3 Waste volumes

The sustainability of the different alternatives was assessed also in terms of wastes (namely materials that would be disposed of in landfills) with the general aim of evaluating, from a quantitative point of view, the pavement scenario that can help in reducing the burden on landfills. As is well known, the use of crumb rubber in asphalt mixtures contributes to avoiding impacts for landfills due to end-of-life tires; the recoverable rubber in a tyre is about 70%. It is worth noting that the processes needed to convert waste vehicle tyres into crumb rubber were allocated to the tyre life cycle and not to the investigated pavement systems. Similarly, the bio-

asphalt (B-B_DG, B-B_PA) allows for recycling the waste olive oil which would be unsuitable for human consumption thus it would be associated with impacts and costs of transport and disposal.

The volume of waste generated by each alternative is calculated by adding the volumes of materials recycled in the pavement system (negative contribution to waste generation) with the volume of RAP to be transported to landfills (positive contribution to waste generation). The sum of these contributions is the indicator “LANDFILL” and it is expressed in m³/m².

2.5 Expected life

In task 4 (Task 4: Derivation of scenarios’ durability and subsequent normalisation of impacts), each impact was divided by the pertaining expected life and the matrix (namely, a column) of the given impact per year was derived. This crucial task was carried out based on the literature and based on Witczack derivation of mixture modulus (*Equation 6*) [33–35].

$$\log_{10} E^* = -1.249937 + 0.02923 \rho_{200} - 0.001767 (\rho_{200})^2 - 0.002841 \rho_4 - 0.058097 V_a - 0.802208 \frac{V_{\text{beff}}}{V_{\text{beff}} + V_a} + \frac{3.871977 - 0.0021 \rho_4 + 0.003958 \rho_{3/8} - 0.000017 (\rho_{3/8})^2 + 0.00547 \rho_{3/4}}{1 + e^{(-0.603313 - 0.313351 (\log f) - 0.393532 (\log \eta))}} \quad \text{Equation 6}$$

In *Equation 6*, E^* is the dynamic modulus [10⁵ psi], η is the asphalt binder viscosity [10⁶ poise], f is the loading frequency [Hz]; furthermore: V_a = air-void content, by volume [%], V_{beff} = effective asphalt binder content, by volume [%], $\rho_{3/4}$ = cumulative percent retained on the 19-mm (3/4 in.) sieve, $\rho_{3/8}$ = cumulative percent retained on the 9.5-mm (3/8 in.) sieve, ρ_4 = cumulative percent retained on the 4.75-mm (No. 4) sieve; and ρ_{200} = percentage passing through the 0.075-mm (No. 200) sieve. The viscosity was assessed through the following model [98]:

$$\log(\eta) = 10.5012 - 2.2601 \cdot \log(\text{Pen}) + 0.00389 (\text{Pen})^2 \quad \text{Equation 7}$$

where Pen (0.1 mm) is the penetration of a standard needle of 100 g which penetrates the asphalt binder for 5 s.

2.6 Data treatment

Based on the matrix of impacts, (cf. **Figure 3**), the corresponding matrix of the normalised values was derived (feature scaling in $0, 1/n$, where n is the number of impacts). Based on this n matrix the base for the comparison of alternative pavement technologies was derived. Under the hypothesis that the impacts are negative impacts (in the sense that the higher the value the poorer the performance), the sum of the n vectors brings to a column where each pavement technology has a given total score. Importantly, as an ancillary result of this task, the breakeven durations were derived (i.e., the expected life corresponding to having the same ranking for all the scenarios).

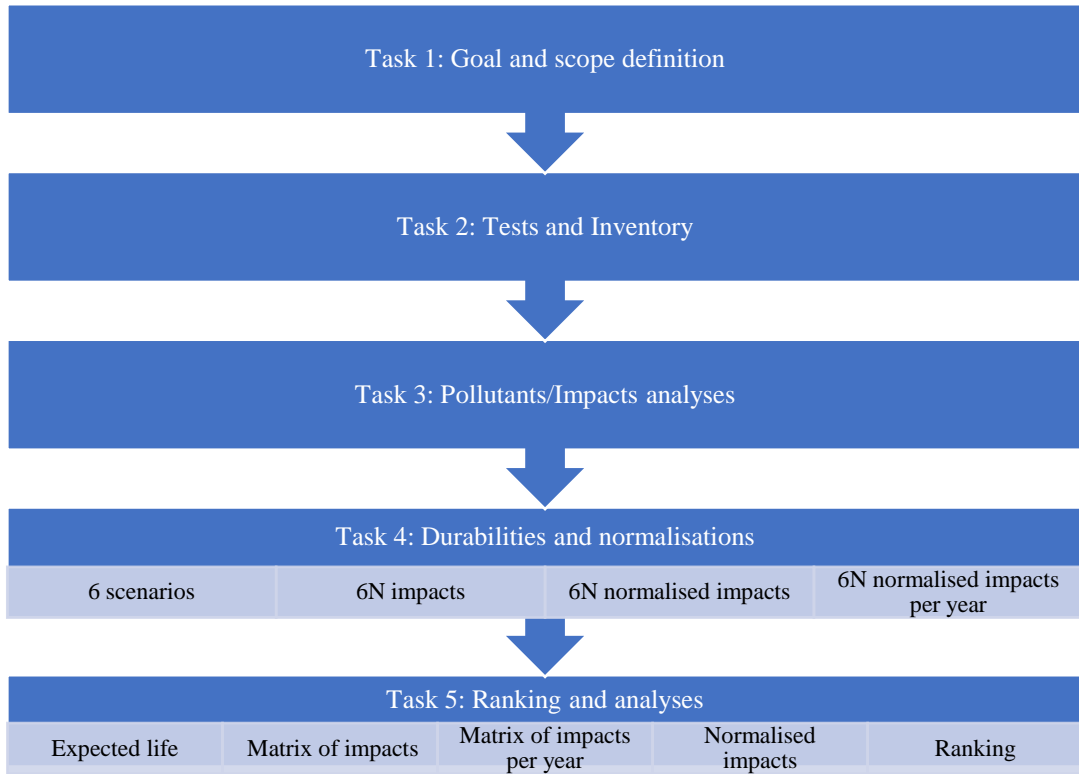


Figure 3. Focus on ranking and analyses.

In more detail, the formalised method is as follows. For the s -th scenario (one scenario per row, overall S scenarios) and for the i -th impact (one impact per column, overall N impacts), the following matrix is derived:

$$X = \begin{bmatrix} x_{11} & & x_{1N} \\ & x_{sj} & \\ x_{S1} & & x_{SN} \end{bmatrix}$$

Under the hypothesis that the N impacts have the same weight, from this matrix the corresponding normalised matrix can be derived, where the given element is defined in $0,1$ the following matrix can be derived:

$$X_N = \left[\frac{x_{sj} - \min_s x_{sj}}{N \cdot (\max_s x_{sj} - \min_s x_{sj})} \right]$$

At the same time, for each scenario, the following vector of the expected lives, EL , is derived:

$$EL = \begin{bmatrix} EL_i \end{bmatrix}$$

Finally, for each s -th scenario, the following running sum is derived:

$$X_{PR} = \left[\sum \frac{(x_{sj} - \min_s x_{sj})}{N \cdot (\max_s x_{sj} - \min_s x_{sj}) \cdot EL_s} \right]$$

Importantly, the value of the expected life vector, EL, that implies that the different scenarios have the same running sum X_{PR} , is the equilibrium expected life (breakeven points) and implies having the same ranking for all the scenarios. The algorithm for the derivation of the equilibrium expected life vector is based on a simple optimization process where: $X_{PR1}=X_{PR2}=\dots X_{PRs}$ that it to say on having the same ranking for all the options.

3. Results and Discussion

3.1 Preliminary analyses

3.1.1 GWP and GER results analysis

Figures 4 to 8 summarise the results obtained for the six scenarios in terms of GWP and GER.

The cradle-to-grave analysis reported in **Figure 4** highlights that the production stage contributes to GWP in a measure always higher than 84% for all scenarios. The results in terms of energy consumption, GER, during the investigated life phases confirm that the contribution of the production phase is always greater than 73%. The contribution of transport activities to emission generation ranges between a minimum of 6% and a maximum of 8%. On site construction processes result in the least impactful activities. This stage is almost the same in all the scenarios, accounting for about 1% for all the technologies.

End-of-life phase contributes to GWP and GER with a magnitude of about 4-7% (in terms of emission generation) and 5-12% (in terms of energy requirement).

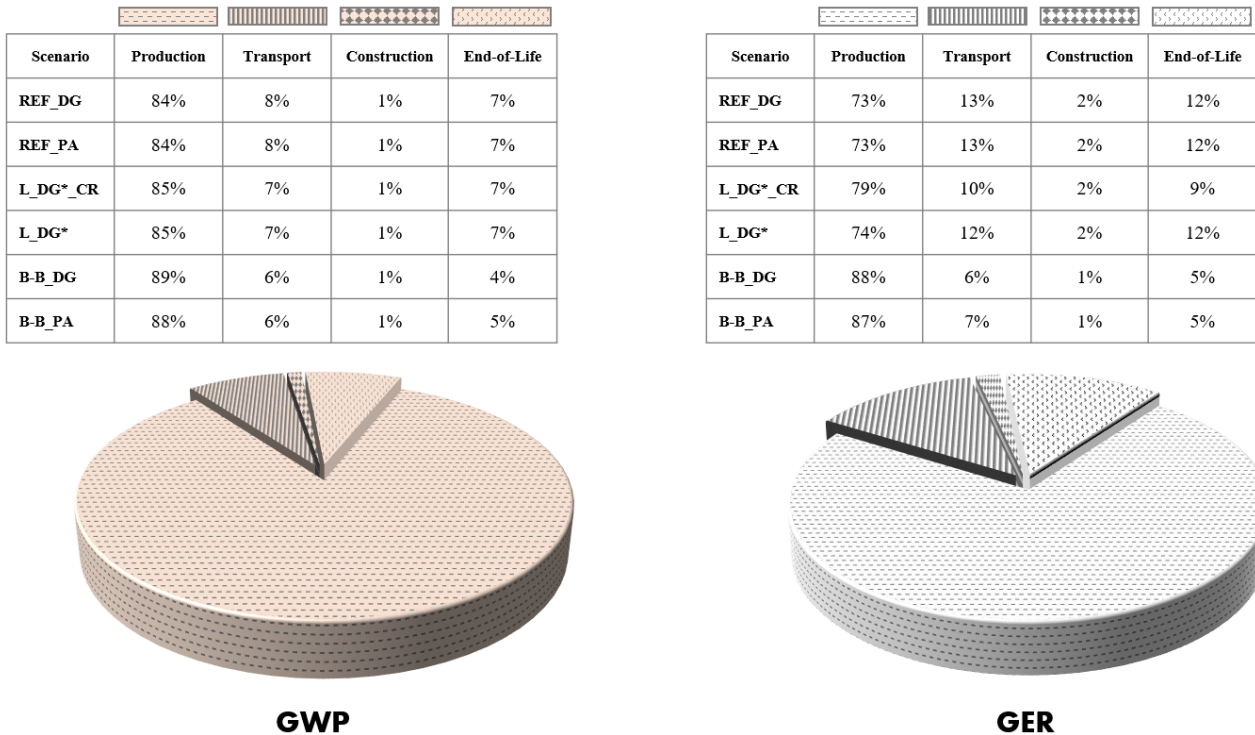


Figure 4. Contribution of each life-cycle stage (cradle-to-grave) to GWP and GER.

Figure 5 and **Figure 6** show LCA results for the selected scenarios with respect to GWP and GER for the functional unit (1 m² of pavement). Data are reported for each life-cycle step (production, transport, construction, and end-of-life) and aggregated in the “cradle-to-grave” indicator. It is easy to note that the production phase is the most impactful of all processes, both in terms of air emissions and energy consumption, regardless of the scenario considered. Construction activities generate 0.08 CO₂-eq/m² and require 1.07 MJ/m² for each scenario.

The scenarios REF_DG, L_DG*_CR, B-B_DG, and B-B_PA are linked to the highest environmental burdens (GWP). In addition, the scenarios including the bio-asphalt mixture are correlated with higher energy requirements.

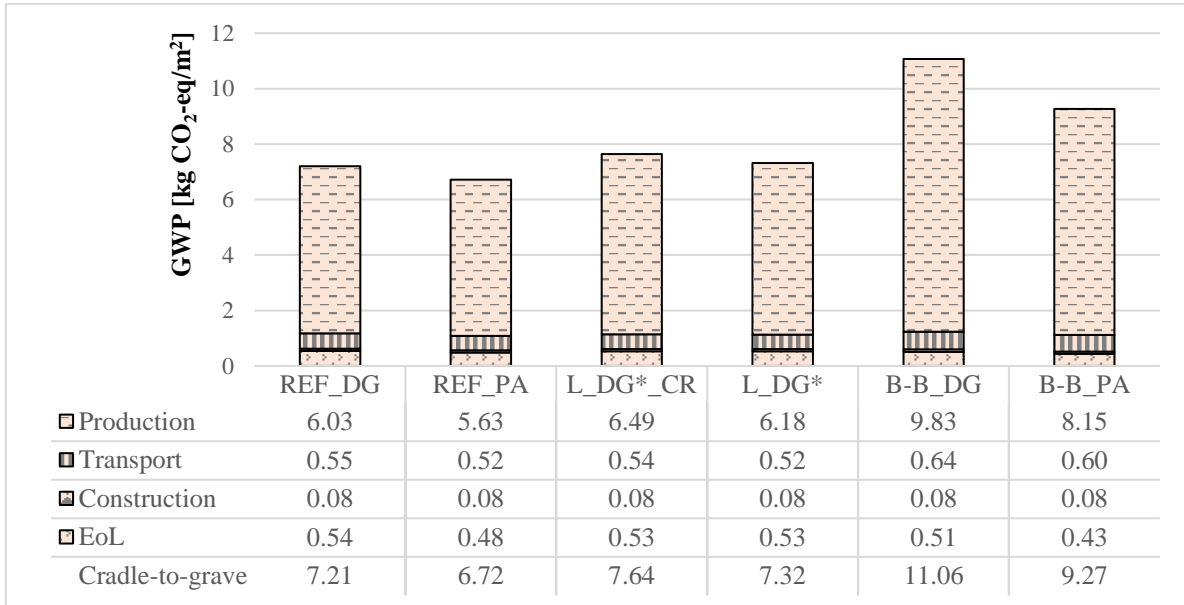


Figure 5. Contribution of each life-cycle stage (cradle-to-grave) to the global warming potential.

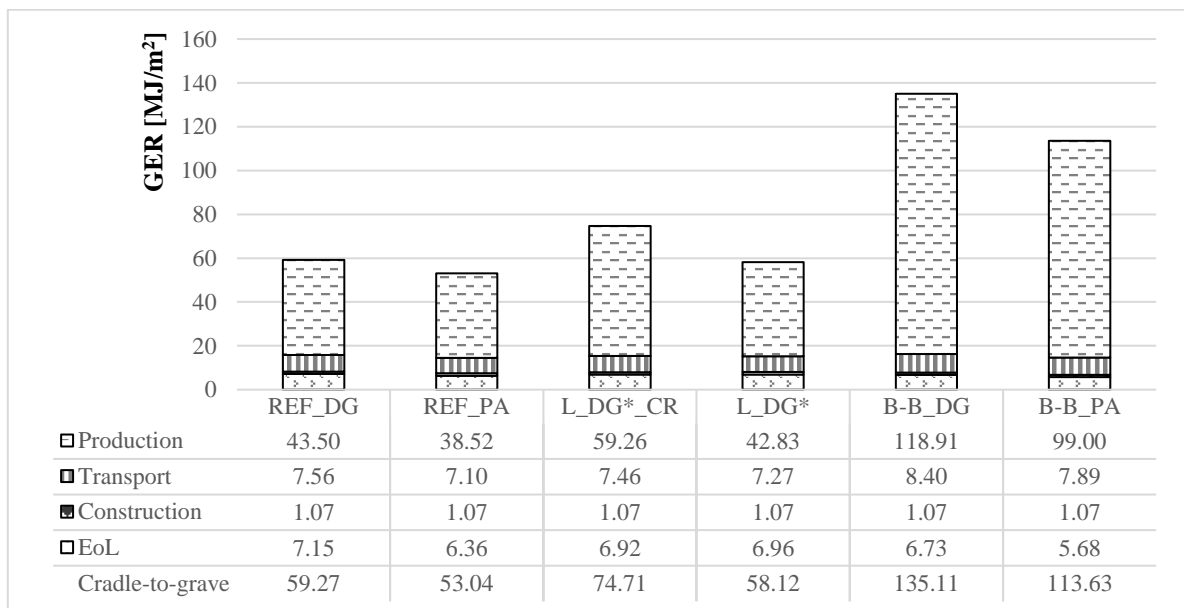


Figure 6. Energy consumption for each scenario and each life-cycle step (cradle-to-grave).

The data reported in the previous figures allow for the following set of comparative considerations in terms of binder type and aggregate gradation:

- i) the contribution of binder type to the generation of air pollutants and energy requirement can be estimated when the aggregate gradation is fixed. The mixtures presenting the same aggregate gradation but different binder types are REF_DG vs B-B_DG, and REF_PA vs B-B_PA. It can be noted that there is a substantial difference between REF_DG and B-B_DG in terms of GWP and GER; in particular, the bio-asphalt dense-graded mixture has the highest impact. More specifically, the highest values are observed for the production process in B-B_DG (bio-binder mixture). When comparing the PA mixtures (REF_PA vs B-B_PA), B-B_PA presents the highest values. Taken together, these results underline that the production of bio-binder mixture accounts

for the highest amounts of air pollutants and the highest energy requirement, regardless of the aggregate gradation. In particular, for the GER, the production process of the bio-asphalt mixture dissipates more energy in the case of the reference mixture.

- ii) The comparisons REF_DG vs REF_PA and B-B_DG vs B-B_PA allow analysing the differences related to the type of aggregate gradation used in the mixture as they have the same type of binder. In particular, these comparisons suggest that GWP and GER are higher for the dense-graded mixtures (REF_DG and B-B_DG) while they decrease when considering the PA mixtures (REF_PA vs B-B_PA). This condition is strictly related to the higher quantity of fine-graded aggregates in dense-graded mixtures. Indeed, the production of fine minerals generates higher quantities of CO₂-eq than the process associated with the production of coarse aggregates. The results obtained for the GER assessment confirm this consideration. In fact, the energy required for the production stage is higher for the dense-graded mixtures as the production of fine aggregates and calcareous filler/ hydrated lime requires more energy than coarse aggregate production (cf. **Table 4**).
- iii) L_DG*_CR and L_DG* present the same aggregate gradation (DG*) and binder (MB) but they differ in the presence of crumb rubber in the mix. This comparison shows that the GWP results are approximately comparable (7.64 vs 7.32 kg CO₂-eq/m², for the L_DG*_CR and the L_DG*, respectively), in particular, GWP values are slightly higher for the L_DG*_CR, when compared with L_DG*. The difference in terms of GER is more significant (74.71 vs 58.12 MJ/m², for the L_DG*_CR and the L_DG*, respectively). These results are affected by the production process of the crumb rubber (type RARX) which generates air pollutants and requires a considerable amount of energy.
- iv) Comparing all the scenarios, results show that the REF_PA (traditional mixture) has the lowest GWP and GER rates whereas the BB_DG (dense-graded bio-asphalt mixture) has the highest impact indexes. The outcomes of life-cycle energy comparative analysis show that material production causes the highest share in bio-binder scenarios (135.11 MJ/m² and 113.63 MJ/m² for BB_DG and BB_PA, respectively); the energy consumed during production activities in the scenarios BB_DG and BB_PA is approximately 2.5 times higher than that required in the production phase of the reference mixture (scenario REF_DG and REF_PA) and about two times higher than the energy required in the production of the asphalt mixture of L_DG*_CR and L_DG*. The energy data do not include the feedstock energy of the bitumen which varies in the range 193.15-223.64 MJ/m² (feedstock energy is proportional to the quantity of bitumen in the mixture).

Concerning the transportation stage, the scenarios BB_DG and BB_PA are associated with the highest share of both environmental and energy impacts, in comparison with the reference scheme and the alternative solution. This last result is strictly related to the fact that bio-binder production implies additional transportation processes compared with the alternatives. For example, in the scenarios BB_DG and BB_PA the transportation of waste olive oil, colophony rosin, crumb rubber, and paraffinic wax to the mixing plant is required to produce bio-binder, instead of the transportation of bitumen involved in the alternative mixtures. Importantly, for colophony rosin, the 0/0 approach was considered, where: 1) the CO₂ uptake during pines growth is equivalent to the CO₂ released at the end of the life [99,100]; 2) the rosin is not involved in CO₂ balance.

On the basis of the above, the production phase requires a specific focus as the production of materials is the life-cycle phase that contributes a significant share of the total environmental and energy burdens. **Figure 7** and **Figure 8** report the contribution of each material to the GWP and GER of the production stage.

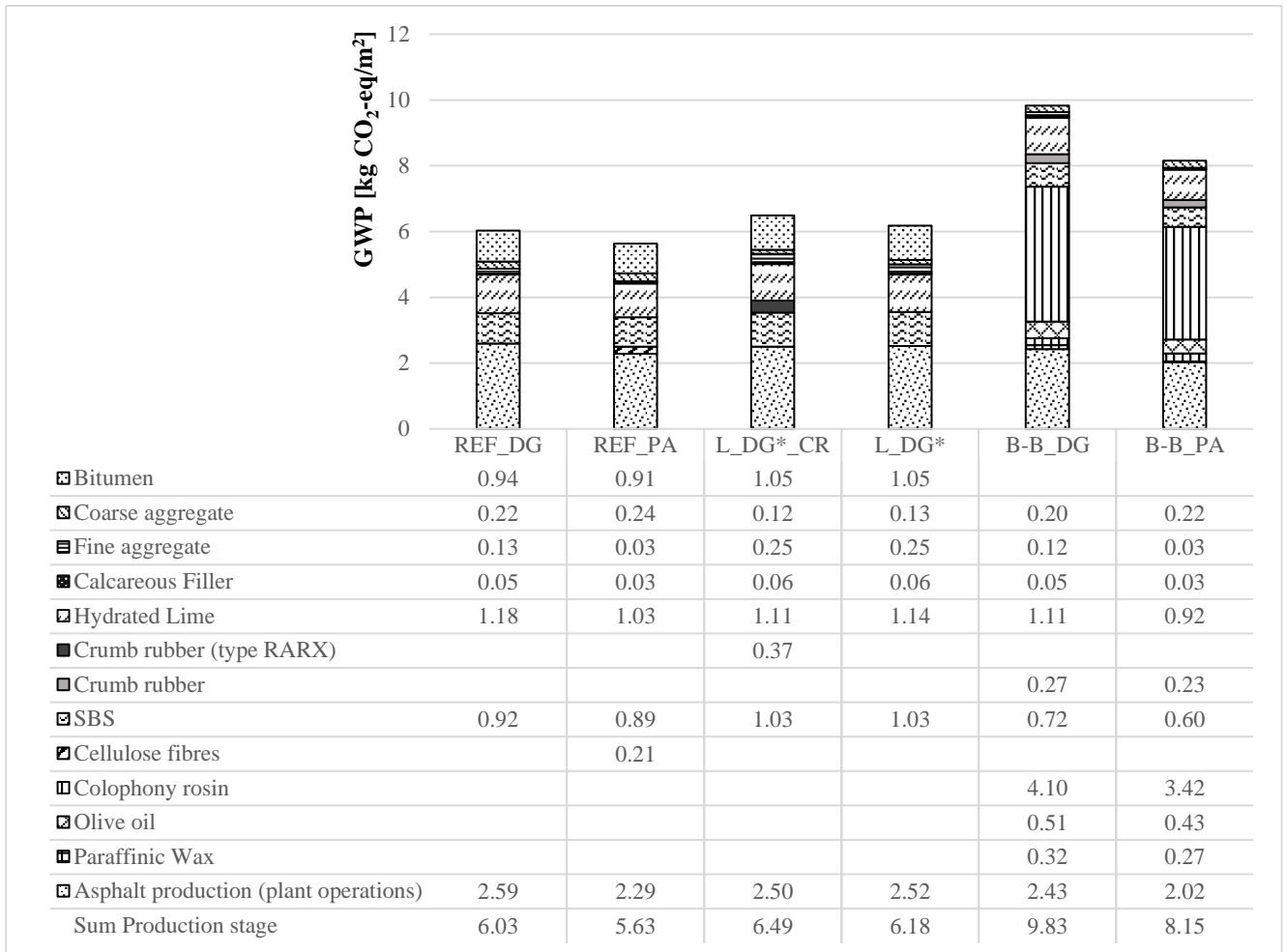


Figure 7. Contribution of the production process of each material (per FU) to GWP.

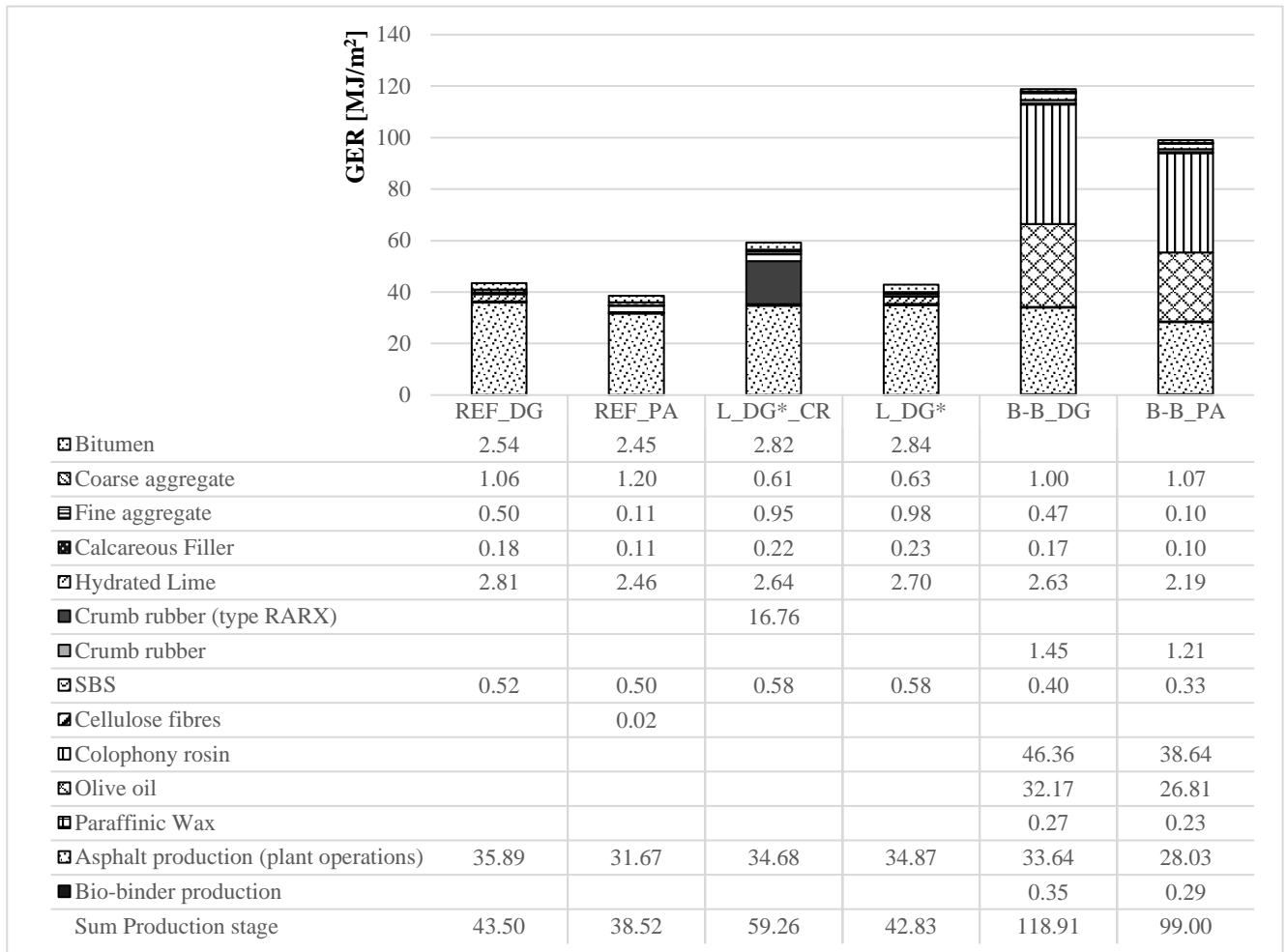


Figure 8. Energy consumption of the production process of each material (per FU).

From **Figure 7**, it can be seen that the most impactful production processes in terms of GWP are the following:

- bitumen, hydrated lime, and SBS production for the reference scenarios (REF_DG and REF_PA) and for the scenario with no crumb rubber (L_DG*);
- the production of bitumen, hydrated lime, SBS, and crumb rubber for the rubberized asphalt (L_DG*_CR);
- the production of colophony rosin, SBS, and hydrated lime for the bio-alternatives (B-B_DG and B-B_PA).

Energy consumption values (**Figure 8**) confirm the GWP findings.

The comparison of the scenarios involving asphalt mixtures (scenarios REF_DG, REF_PA, L_DG*_CR, and L_DG*) confirms the results of the literature that state that bitumen production is generally associated with the highest energy and carbon footprints [51,52]. In scenarios B-B_DG and B-B_PA the replacement of the bitumen with bio-binder allows for preserving the consumption of natural non-renewable resources. Nevertheless, the production of bio-binder components involves a significant contribution to the generation of emissions to air and requires high energy consumption; also waste olive oil contributes to this increase (an energy value of about 37.66 MJ/kg was assumed for this product [76]). Furthermore, the scenarios B-B_DG and B-B_PA imply a share of energy attributable to bio-binder production (mixing of bio-binder components). The use of bitumen in the asphalt mixture including crumb rubber (dry method) involves lower environmental and energy consumption impacts when compared with the bio-alternative (L_DG*_CR vs B-B_DG); in fact, the sum of the impacts related to the production of both bitumen and crumb rubber is lower (76% in terms of GWP and 83% in terms of GER, respectively) than the sum of the impacts associated with the bio-binder

components. Comparing REF_DG with B-B_DG (both DG) it is possible to note a significant difference in terms of binder production; in fact, the production of bitumen generates 0.94 kg CO₂-eq/m² and requires 2.54 MJ/m², the production of bio-binder is associated with the emission of 5.93 kg CO₂-eq/m² and the consumption of 114.29 MJ/m².

Concerning the production of natural aggregates (calcareous filler, coarse and fine aggregates), GWP ranges between 0.3 and 0.4 kg CO₂-eq/m² for the open- and dense-graded mixture, respectively. The energy consumed in the aggregate production process is about 1.3-1.4 MJ/m² for the PAs and 1.6-1.8 MJ/m² for the DGs. However, the contribution of the aggregate production process to the GWP and GER rates of the production stage is about 3-7% and 1-4% in terms of emission generation and energy consumption, respectively.

The mixing plant operations (including the heating of the aggregates and their mixing with binders) generate approximately 2.02-2.59 kg CO₂-eq/m² and consume about 28.03-35.89 MJ/m². Plant operations are the most impactful process for the traditional asphalt mixture and the rubberized asphalt mixture, in terms of energy requirement.

3.1.2 DALY results analysis

Figure 9 summarizes the results obtained for the human health impact category investigated. The graphs show the values of DALY over time for each scenario, taking into account the service life of each pavement. The DALY values suggest that the rubberized asphalt (L_DG*_CR) yields the lowest noise impact. In particular, the reduction in DALY is approximately 31% and 25% lower, when compared with the traditional dense-graded mixture (REF_DG) and with the mix with no crumb rubber (L_DG*).

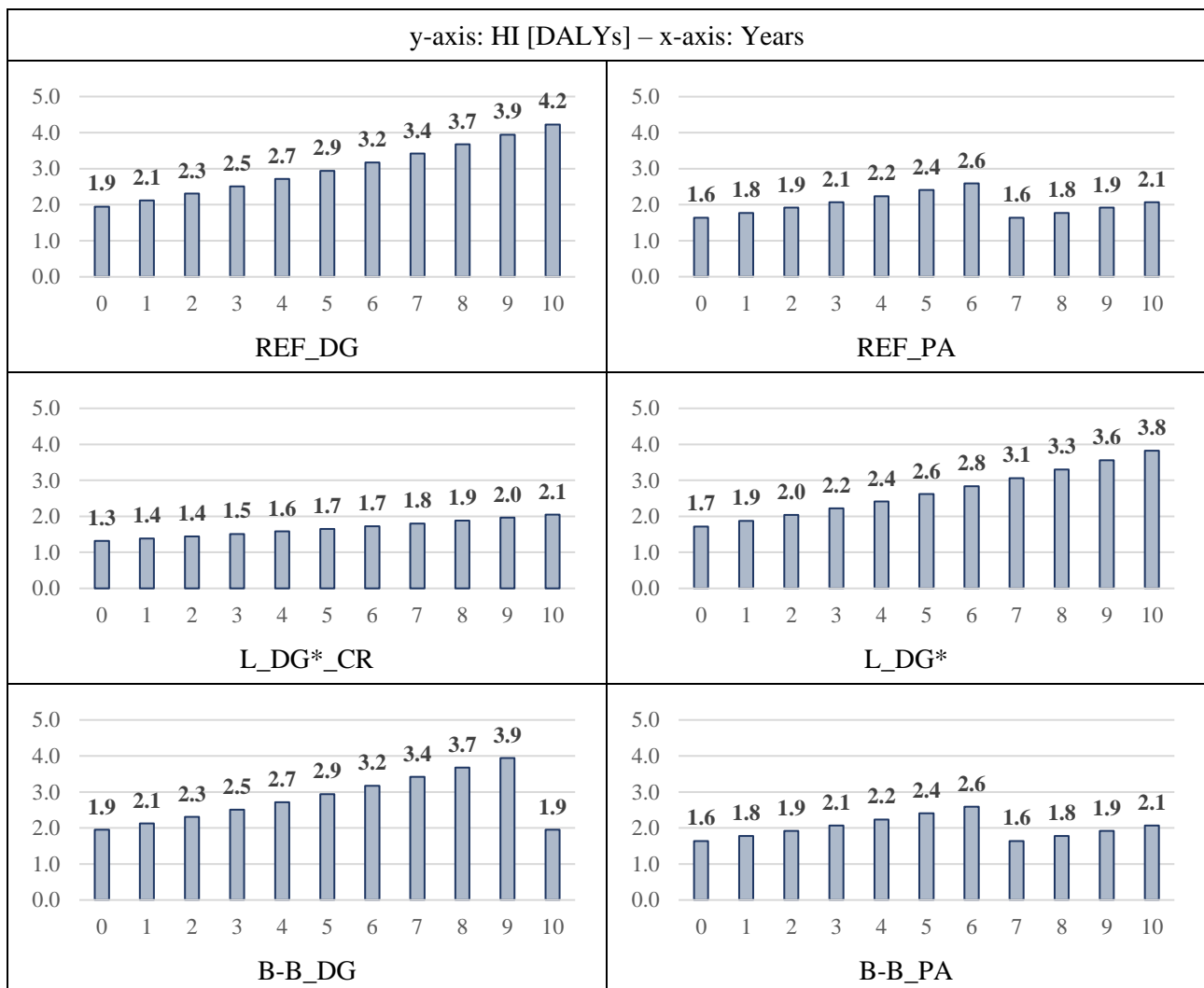


Figure 9. DALY over time for each scenario.

3.1.3 Waste volumes analysis

Figure 10 reports the values of waste volumes for each investigated scenario. Negative quantities refer to waste materials while positive quantities refer to the RAP, disposed into landfills at the end of the life cycle. It easy to note that the traditional dense-graded mixture (REF_DG) and the dense-graded mixture with no crumb rubber (L_DG*) present the highest rate. The lowest impacts are recorded for the rubberized asphalt and for the bio-asphalt. In particular:

- Scenario_1 allows reusing 0.013 m³ of tyres per m².
- Scenario_2 and 2* allow reusing 0.01 and 0.008 m³ of tyres per m², respectively.
- Scenario_2 and 2* allow reusing 0.0009 and 0.00078 m³ of waste olive oil per m², respectively.

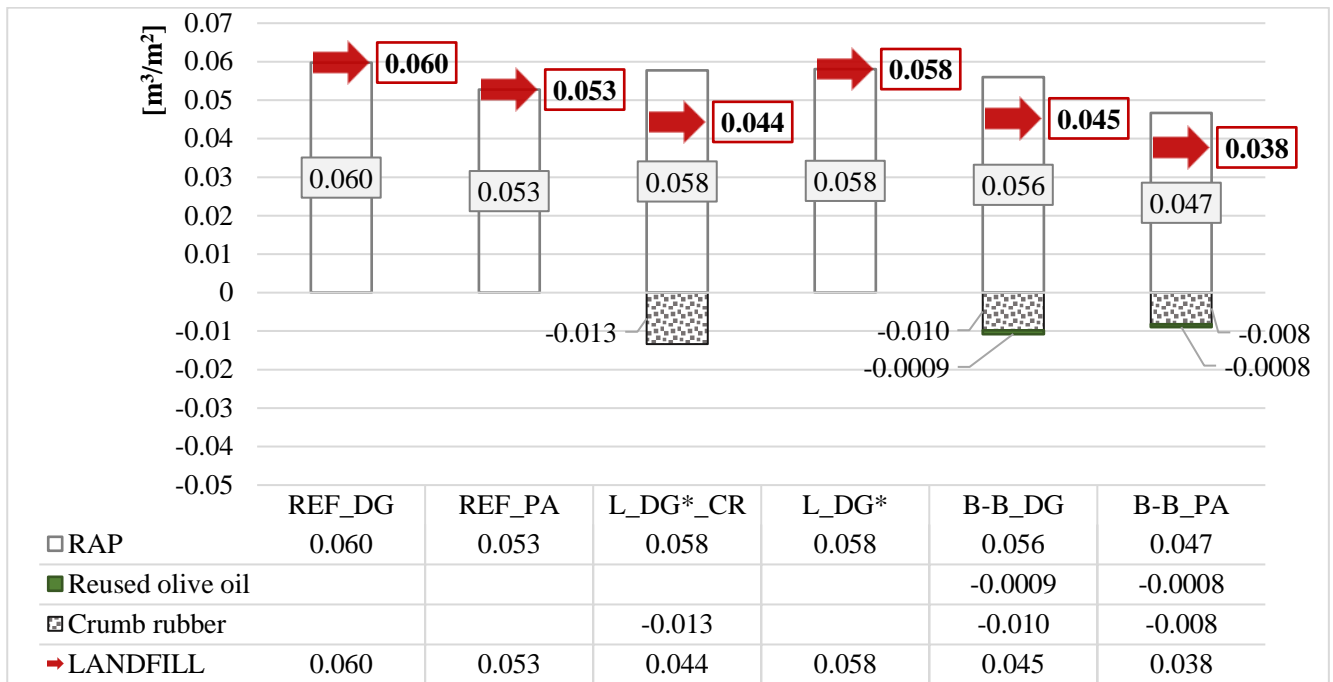


Figure 10. Waste volumes for each scenario.

3.2 Normalising and aggregating

Table 9 illustrates the moduli of each mixture.

Table 9. Moduli for each mixture.

	REF_DG	REF_PA	L_DG*_CR	L_DG*	B-B_DG	B-B_PA
E* [Mpa]	2,851	1,044	2,611	2,605	2,171	1,278

Based on the equations and methods illustrated in sections 3.7 and 3.8 and on the moduli in **Table 9**, the following vector EL of the expected life was obtained (cf. [64]):

$$EL = \begin{pmatrix} 10 \\ 6 \\ 10 \\ 10 \\ 9 \end{pmatrix} \begin{matrix} REF_DG \\ REF_PA \\ L_DG_*_CR \\ L_DG_* \\ B-B_DG \end{matrix}$$

Table 10 A summarises the impacts for each scenario in terms of GWP (kg CO₂-eq/m²), GER (MJ/m²), DALY (years/m²), and LANDFILL (m³/m²).

Table 10. Summary of impacts (A) and ranking without expected life (B), with expected life (C) and with equilibrium expected life (D).

A	GWP	GER	DALY	LANDFILL
REF_DG	7.2	59.3	33.0	0.06
REF_PA	6.7	53.0	14.63	0.05
L_DG*_CR	7.6	74.7	18.32	0.04
L_DG*	7.3	58.1	29.46	0.06
B-B_DG	11.1	135.1	28.74	0.05
B-B_PA	9.3	113.6	14.63	0.04

B	GWP	GER	DALY	LANDFILL	Expected life	X _{PR}	Ranking
REF_DG	0.03	0.02	0.25	0.25	not considered	0.55	5th
REF_PA	0.00	0.00	0.00	0.17		0.17	best
L_DG*_CR	0.05	0.07	0.05	0.08		0.24	2nd
L_DG*	0.03	0.02	0.20	0.23		0.48	4th
B-B_DG	0.25	0.25	0.19	0.09		0.78	worst
B-B_PA	0.15	0.18	0.00	0.00		0.33	3rd

C	GWP	GER	DALY	LANDFILL	Expected life considered	X _{PR}	Ranking
REF_DG	0.00	0.00	0.25	0.07	10	0.31	2nd
REF_PA	0.16	0.08	0.13	0.25	6	0.62	4th
L_DG*_CR	0.02	0.04	0.00	0.00	10	0.06	best
L_DG*	0.02	0.00	0.21	0.07	10	0.30	3rd
B-B_DG	0.18	0.20	0.25	0.03	9	0.66	worst
B-B_PA	0.25	0.25	0.08	0.07	6	0.65	5th

D	GWP	GER	DALY	LANDFILL	Equilibrium expected life	X _{PR}	Ranking
REF_DG	0.00	0.01	0.25	0.25	9	0.50	-
REF_PA	0.19	0.01	0.05	0.25	8	0.50	-
L_DG*_CR	0.20	0.11	0.07	0.12	9	0.50	-

L_DG*	0.06	0.00	0.21	0.24	9	0.50	-
B-B_DG	0.18	0.23	0.09	0.00	13	0.50	-
B-B_PA	0.25	0.25	0.00	0.00	11	0.50	-

While **Table 10 A** illustrates the results in terms of impacts/m², **Table 10 B** illustrates the corresponding values after the normalisation in (0, 0.25), due to the need for having scores (X_{PR}) in (0,1). **Table 10 C** focuses on the same normalised impacts expressed in terms of impact/year/m². Finally, in **Table 10 D** the same impacts (impact per year per square meter) are derived under the assumption of having the same score (i.e., 0.5). In other terms, they refer to the equilibrium expected life, i.e., the expected life needed to have the same overall score (X_{PR}).

It is possible to observe that:

- the best performance can be associated with the scenario L_DG*_CR. In particular, this pavement technology allows optimizing two impact indicators: the DALY and the LANDFILL. This result suggests that rubberized asphalt can be correlated with the decrease in the human health impact of traffic noise and with the optimization of the production of waste volumes. At the same time, its gradation and bitumen percentage lead to a high modulus. Indeed, due to the low value of the percent retained to the 9.5 sieve and to the (consequent) high value of the effective bitumen volume, the corresponding modulus is high and this implies a higher expected life. It is worth noting that according to several authors (e.g., [101]) the CR content would imply *per se* a higher expected life but this factor was not considered. Furthermore, it is noted that the durability of this mixture is crucial because this solution, ranked first when considering its durability, would rank second without taking into account its durability.
- The worst performance is associated with scenario B-B_DG, (where the bio-binder was used) regardless of the information on the durability. This scenario has three main drawbacks: the energy required (among the highest ones), the corresponding carbon footprint, and the acoustic performance. This is mainly due to the colophony, which amounts to 51% of the binder (w/w) and to the corresponding low viscosity of the binder, which, in turn, affects the expected life. This latter is the crucial parameter and is responsible for the unsatisfactory ranking. Future studies will be focused on increasing this binder performance and consequently the mixture expected life.
- The traditional dense-graded asphalt friction course (REF_DG) allows obtaining optimized results in terms of reduction in GWP and GER but a decrease in terms of acoustic performance.

At the same time, in order to have *N ex aequo* results, the equilibrium vector EL of the expected life illustrated in **Table 10 D** would be needed. This vector is pivotal because it represents the targets to pursue in order to allow the existence of competitive equilibria between eco-solutions and traditional pavement technologies.

4. Limitations of the study and conclusions

In this study, a comprehensive analysis was carried out dealing with different pavement technologies including six different types of mixture for the friction course. Traditional friction course mixtures (dense-graded and open-graded mixtures) were compared with two innovative solutions including the use of crumb rubber (dry method) and a solution involving 100% replacement of bitumen (bio-binder produced by mixing different materials including wastes such as waste olive oil and crumb rubber from end-of-life tires - wet method). The analysis covers all the activities related to raw materials acquisition and composite materials production, construction processes, and transportation operations. The study discusses and highlights differences in terms of energy consumption, GHG emissions, noise impact, and landfill-related impacts, with the general aim of quantifying the magnitude of the contribution that each different construction material and process has in producing “burdens”.

This study has the following limitations:

- Selection and numerosity of impacts and scenarios. Even if the methodology was set up for general purposes the selection of the scenarios was carried out based on the consideration of project-specific targets. Future studies will be devoted to the consideration of further impacts.
- Normalisation. The choice of an internal normalisation method could affect the comprehensiveness of the study because of the consideration of selected scenarios that could be non-representative of more complex scenarios (see also [102]).
- Weighting. This applies also weighing, where the choice of equal weights for all the impacts could neglect particular issues or contingencies (e.g., collateral damages arising from rosin extraction).
- Aggregation. The aggregation process was carried out based on the methodology set up. Future research will address the study of optimal aggregation algorithms.
- Shortage of components and materials. The shortage of virgin/raw materials (e.g., oil-based materials such as bitumen) could lead to the need for considering supplementary impacts, introducing different weights, and/or setting up diverse aggregation criteria.

The main findings of the study are as follows:

- The technology where the mixture includes crumb rubber (dry method, rubberized asphalt) has a very low environmental (GWP) and energetic (GER) impact when compared with the bio-binder solution, regardless of aggregate gradation.
- The Scenario including the bio-binder generates significant amounts of air pollutants, due to the production process of input materials. Indeed, while this technology (bio-binder without bitumen addition) allows preserving the consumption of bitumen (given its 100% replacement in asphalt mixture), this scenario drawback is related to the fact that the production of bio-binder components involves significant contributions in terms of emissions to air and energy requirements. Taken together, these study findings suggest that the environmental impacts of specific materials where biomass is used cannot be generalised as negligible. In other terms, these solutions are not necessarily a panacea for a particular set of problems. These latter should be systematically investigated because the implementation of biomass and bio-binders could not be considered beneficial to the environmental system under all conditions.
- In the pursuit of promoting the challenge towards more effective solutions, the concept of equilibrium expected life (breakeven points) was introduced and the corresponding algorithm for its derivation was set up. This expected life could act as an “engine” towards industrial solutions able to prevent severe impacts on the climate system without neglecting the importance of crucial parameters such as the expected life. In other terms, this could help bridge the gap between the asphalt industry (known, traditional solutions), road agencies, and academia/ research (noise-oriented, sustainability-oriented solutions).
- Finally, the non-panacea paradigm above could itself be invalidated by contingencies such as oil shortage, as mentioned above. Under such conditions, the use of waste materials and biomasses could be crucial. This implies that LCA-type impacts should be always complemented by supplementary impacts and indicators aiming at representing the need for a system redundancy to withstand unexpected contingencies.
- Some of the concepts above apply also to the comparison between traditional dense-graded (e.g., DG) and open-graded friction courses (e.g., PA). Indeed, while the consequences on bystanders’ health due to traffic noise are mitigated by the use of PA-like technologies, GER and GWP appear higher for PAs. Additionally, this underlines the limitations of aggregated data and consequent ranking, which is one of the limitations indicated above.

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