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ENVIRONMENTAL IMPACT ASSESSMENT OF PAVEMENTS WITH THE ADDITION OF RECYCLED POST-CONSUMER POLYETHYLENE TEREPHTHALATE (RPET) THROUGH THE LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

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Al principio existía la Palabra, y la Palabra estaba junto a Dios,
y la Palabra era Dios.
Al principio estaba junto a Dios.
Todas las cosas fueron hechas por medio de la Palabra
y sin ella no se hizo nada de todo lo que existe.
En ella estaba la vida,
y la vida era la luz de los hombres.
Evangelio según San Juan. Cap. 1

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Abstract

The present study presents a cradle-to-built life cycle assessment (LCA) for a road pavements structure of hot mixed asphalt (HMA) with recycled post-consumer polyethylene terephthalate (RPET) addition as aggregate substitution through the "dry" process using a comparison analysis of 1 m^2 built pavement as a functional unit, using the Brazilian "National Design Methodology" (MeDiNa) for layer dimensioning integrating the mechanical and functional parameters of the mixes, in contrast with conventional mix variant. The geotechnical data was obtained from the studies of Ferreira et al (2022) and Arao et al (2017) for the HMA mixes, and Carvalho et al (2016) for the alternative base course proposal. A complementary analysis between the production of 1 ton of each HMA mixes was also developed, as a declared unit comparison point, assessing the process contribution. The Tool TRACI 2.0 for reducing and assessing chemical and other environmental impacts was applied for each alternative, assessing the impacts into categories such as acidification, eutrophication, freshwater ecotoxicity, global warming potential, human health, ozone depletion, and smog formation. The life-cycle impact assessment results were interpreted through internal normalization criteria and weighting rule, obtaining an environmental score for each alternative, and allowing a straightforward stakeholder interpretation. Considering the better mechanical properties and overall functional performance of the HMA + RPET mixes for the surface course, the functional unit comparison resulted in savings in almost all environmental impact categories for each square meter of pavement constructed and ready to use, with an overall layer thickness optimization effect that carries a cascade of upstream resource and emissions savings. This effect was explored with the sensibility analysis of net PET mass added by FU (functional unit), with an equilibrium mass identified for global warming potential and environmental score, establishing the ground for sustainable pavement definition and delimitation. It establishes a novel sustainability criterion for pavement structures with the addition of plastic post-consumer, integrating the mechanical and environmental performance and allowing for guidance in future plastic-pavement research and develop of paving project in the Brazilian context.

Resumo

O presente estudo apresenta uma avaliação do ciclo de vida (ACV), da origem à construção para uma estrutura de pavimentos rodoviários de Concreto Betuminoso Usinado a Quente (CBUQ) com adição de polietileno tereftalato reciclado pós-consumo (RPET) através do processo "seco" utilizando uma análise de comparação de 1 m^2 de pavimento construído como unidade funcional, utilizando o “Método de Dimensionamento Nacional" (MeDiNa) para o projeto da estrutura de pavimento integrando os parâmetros mecânicos e funcionais das misturas, em contraste com a variante de mistura convencional. Os dados geotécnicos foram obtidos dos estudos de Ferreira et al (2022) e Arao et al (2017) para as misturas de CBUQ com RPET, e Carvalho et al (2016) para a proposta de curso de base alternativa. Uma análise complementar entre a produção de 1 tonelada de cada mistura CBUQ também foi desenvolvida como unidade declarada, avaliando a contribuição do processo. A Ferramenta TRACI 2.0 para redução e avaliação de impactos químicos e outros impactos ambientais foi aplicada para cada alternativa, avaliando-se os impactos em categorias como acidificação, eutrofização, eco toxicidade em água doce, potencial de aquecimento global, saúde humana, destruição da camada de ozônio e geração de poluição. Os resultados da avaliação de impacto do ciclo de vida foram interpretados por meio de critérios internos de normalização e regra de ponderação, obtendo-se uma pontuacão ambiental para cada alternativa e permitindo uma fácil interpretação das partes interessadas. Considerando as melhores propriedades mecânicas e o desempenho funcional geral das misturas CBUQ + RPET para o revestimento, a comparação das unidades funcionais resultou em economia em quase todas as categorias de impacto ambiental para cada metro quadrado de pavimento construído e pronto para uso, com um efeito geral de otimização das espessuras das camadas, carregando uma cascata de economia de recursos e emissões. Esse efeito também foi explorado com a análise de sensibilidade da massa de PET adicionada por unidade funcional, com uma massa de equilíbrio identificada para o potencial de aquecimento global e pontuação ambiental, estabelecendo o terreno para a definição e delimitação de pavimento sustentável. Foi possível estabelecer um novo critério de sustentabilidade para estruturas de pavimentos com a adição de plástico pós-consumo, no qual integra o desempenho mecânico e ambiental, bem como sugere uma direção em futuras pesquisas na área de pavimentação com a inserção de plásticos e desenvolvimento de projetos rodoviários com materiais alternativos no contexto brasileiro.

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TERMS USED

CR	Crumb Rubber
CIR	Cold In-Place Recycling
DU	Declared Unit
ELT	End-of-Life Tires
ES	Environmental Score
FU	Functional Unit
GHG	Greenhouse Gases
GWP	Global Warming Potential
HMA	Hot Mix Asphalt
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PR	Plastic Recyclates
RAP	Recycled Asphalt Pavement
RCA	Recycled Concrete Aggregate
RPET	Recycled Post-consumer Polyethylene Terephthalate
SMA	Stone Mastic Asphalt
WMRA	Warm Mix Recycled Asphalt

1 INTRODUCTION

1.1 Problem Statement

Due to their large extents and high consumption of resources, road pavements are the focus of researchers who seek the development of alternative materials for asphalt mixtures, with sustainable characteristics natural resources use, but also envisioning the improvement of mechanical parameters and durability of composites, minimizing maintenance, and ensuring long-term cost-benefit.

The present study has been developed to complement research in the area of new geotechnical materials and the use of non-conventional materials, as alternative options for asphalt mixture designs, developed to meet normative requirements of performance and mechanical resistance, in addition to providing alternative asphalt pavements considered "environmentally friendly" for the Brazilian market, highly demanding of road structures of large extensions and regions with limitations of natural resources

Incorporating recycled post-consumer polyethylene terephthalate (RPET) in hot mix asphalt (HMA) through the “dry” process as aggregate replacement has shown increased the pavement performance, better mechanical parameters, superior aging and moisture damage resistance, and asphalt–aggregate adhesion. Although it sets a premise for a new life cycle use for the RPET as a sustainable and environmentally friendly component of asphalt pavements, with an optimized thickness effect and potentially better damage resistance improvement, the present LCA study aims to establish a standpoint for the RPET effects on the environmental impacts of these pavement alternatives, integrating the results of Ferreira et al (2022) and Arao et al (2017) for the geotechnical HMA data, with two comparison points: (a) a declared unit of 1 t of HMA mixes, for reference analysis and (b) the main LCA analysis defining a functional unit of 1 m^2 of pavement structure with the use of the Brazilian “National Design Methodology” (MeDiNa) for layer dimensioning, for a primary road system, medium traffic conditions and a 10 year analysis timelapse.

1.2 Objectives

1.2.1 General Objective

Perform a comprehensive life-cycle assessment for the sustainable pavement alternatives with Hot Mix Asphalt mixtures with addition of recycled post-consumer polyethylene terephthalate, with the use of primary data, adapted to a Brazilian context.

1.2.2 Specific Objectives

– Define declared and functional units for the LCA, with consideration of mechanical and performance parameters for each HMA mixture, under the National Design Methodology MeDiNa for pavement structure design;
– Assess the environmental impacts of the HMA mixtures with RPET addition in comparison with the conventional variants using the tool for the reduction and assessment of chemical and other environmental impacts “TRACI 2.0”;
– Stablish the internal normalization and weighting for single environmental score criterion for the declared and functional units, in accordance with the life-cycle assessment ISO normative and stakeholder perspective, for better decision-making process, comparative analysis and easy comprehension of results;
– Perform a sensitivity analysis exploring the tendency of the impact in global warming potential (GWP) and environmental score by the increase of RPET added in each declared and functional unit, allowing for easy sustainability metric assessment of pavement with recycled post-consumer plastics;

1.3 Scope and dissertation structure

The present dissertation is divided by the following sections:

1. Introduction;
2. Literature review;
3. LCA Methodology;
4. Results;
5. Discussion;
6. Conclusion and Recommendations;
7. References.

2 LITERATURE REVIEW

2.1 Sustainable Pavements with new materials

Circular economy targets and overall sustainability are current goals in global economies, and the use of cleaner practices such as abatement of emissions, use of waste or bio-based materials and reduced manufacturing temperatures must be constantly explored and developed in infrastructure technologies, such as roadway asphalt pavements, due to its extensive dimensions and being resource intensive. The fuel used in the burners that heat and dry the aggregates is the main source of emissions. Also, the aggregates moisture content is an important parameter that influences the energy consumption. On the other hand, the energy consumption, and emissions to produce Portland cement mixtures are related to the process of cement production, used in rigid pavement projects (Thives and Ghisi, 2017). This has attracted great attention from researchers focusing on developing sustainable pavements with alternative materials that could serve as an environmentally friendly method to dispose of such waste while simultaneously producing high-quality pavements. (Mattinzioli et al., 2021; Osorto and Casagrande, 2023).

Alternative material's proposal for pavement structures should follow a cost-effective analysis and socioenvironmental studies to support the technology implementation and feasibility in public and private projects. The use of alternative materials more environmentally advantageous might not be preferred to its conventional solution due to budgetary constraints, lack of solid supply market or due to disadvantages in mechanical performance. (Santos et al., 2017). Nonetheless, important advances have been reported in the recycling of waste materials at the end-of-life stage, representing a second life with "free environmental burden," or a significant less resource intensive alternative to its virgin analog.

2.1.1 Use of alternative materials in Paving Industry

Reclaimed Asphalt Pavement (RAP) (Leng et al., 2018b; Piao et al., 2021), Recycled Concrete Aggregates (RCA) (Gravina et al., 2021), Crumb Rubber (CR) from End of Life Tires (ELT)(Ge et al., 2016; Gibreil and Feng, 2017) and Plastic Recyclates (PR) (Ben Zair et al., 2021; da Silva et al., 2021; Santos et al., 2021) are common research materials that have shown promising results in improving the mechanical characteristics of pavements, increased its durability and offer a sustainable alternative for roadway projects to consider in the planning stage, revealing urban mining opportunities and market niche openings.

RAP has been extensively characterized for its use in bituminous mixtures, with up to 60% content in Hot Mix Asphalt (HMA) preparation, with a similar behavior of that of a conventional high modulus mixture. It also represents one of the most re-used construction products worldwide; in 2018, approximately 88% wt. and 72% wt. of RAP were used in USA and Europe, respectively, as aggregates for Hot, Warm and Cold Asphalt Mixtures and for unbound layers (Tarsi et al., 2020). The RAP has also been combined as aggregates in Warm Mix Recycled Asphalt (WMRA), at a lower temperature than a HMA, showing better results in terms of water sensitivity and similar fatigue resistance. (Dinis-Almeida et al., 2016; Valdés et al., 2011). Its use as an alternative material for road base construction has been extensively studied, both in aggregate substitution, but more favorable when stabilized with cement. (Taha et al., 2002).

Recycled concrete aggregates and waste materials, such as construction and demolition wastes, brick powder and fly ash has been tested as alternative source of filler in asphalt mixtures, in contrast of the conventional natural alternatives such as limestone. Its use can bring benefits in shorter transportation distances, as it can be obtained locally; furthermore, the presence of calcium oxide in the construction and demolition waste increases adhesion and water induced stripping resistance, potentially replacing the effect of limestone, Portland cement and hydrated lime. (Antunes et al., 2017; Chen et al., 2011).

Crumb Rubber (CR) has been extensively studied as an asphalt binder modifier in HMA, demonstrating an improvement on physical properties, resistance to moisture damage and permanent deformation. Gained popularity in paving industry and is a co-product from the mechanical size reduction of end-of-life tires (ELT) and it can be added to the asphalt mixtures through “wet” or “dry” production process and respectively added to base Asphalt as a modifying agent or in hot mix plants as an additional aggregate fraction. These mixtures can also be considered more or equally beneficial that the RAP HMA mixtures at lower quantities (e.g., 15%). (Ge et al., 2016; Gibreil and Feng, 2017; Mattinzioli et al., 2021).

Plastic Recyclates (PR) have shown particulate interest among researchers due to its high demand and value on the market, as well as the ecological burden that its disposal presents to stakeholders. The use of Polyethylene in HMA has proven to be potentially advantageous in enhancing the resistance to moisture damage, especially for regions where the pavement deterioration process is associated with an intensive rainfall regime, thus demonstrating this application’s practical feasibility in concrete asphalt paving. (Ferreira et al., 2022). The process of inclusion of the PR divided in “dry” and “wet” process, in which the first one is defined as the addition of the PR in the final segment of the mixing process, as another aggregate; while the second one combines the PR with the asphalt binder and blends it, acting as a plastic modifier for the asphalt. (Ben Zair et al., 2021).

2.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is the compilation and assessment of a product's inputs, outputs, and environmental impacts during its life cycle (see Figure 1), providing a systematic perspective of the environmental factors, resources invested, residues and emissions for one or more product systems. (ISO 14040:2006, 2010; ISO 14044:2006, 2010). In addition, LCA is one of several environmental management techniques, in addition to risk assessment, environmental performance assessment, environmental audit and environmental impact assessment. The fundamental difference between LCA as an environmental management technique compared to others is the definition of the boundaries of the evaluated system. In an LCA, the boundary is defined by the stages of life of a specific product understood within a functional unit, quantifying its performance; however, in an environmental impact assessment, the boundary is defined by the stages of life of a project in a specific location, the latter being the most important characteristic of the location for the assessment of the magnitude and impact of activities on the environment.

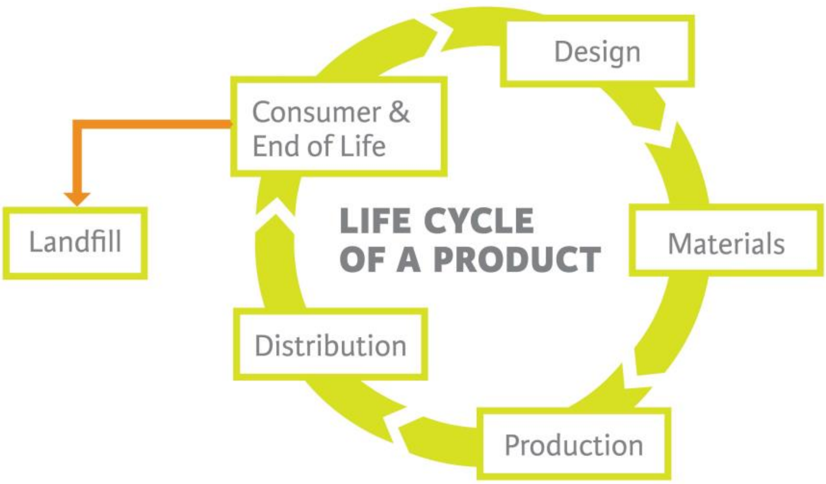


Figure 1: Life Cycle of a Product. By Unknown Author is licensed under CC BY-SA

2.2.1 Stages of LCA

LCA follows an iterative flow process in which a system scope is defined together with spatial and temporal boundaries; the Life Cycle Inventory (LCI) is detailed for each of the product process and upstream stages; a Life Cycle Impact Assessment methodology is applied for environmental impact characterization and ponderation; and a final interpretation step determines the fulfillment of the proposed scope for the LCA. This iterative process is presented in Figure 2.

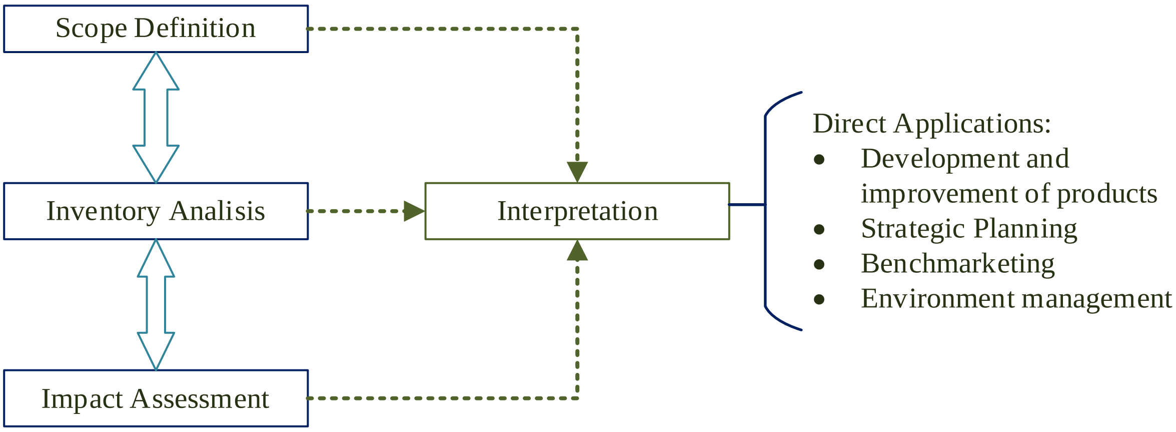


Figure 2: Life cycle assessment structure and applications.

The scope of the product system requires the selection of the main processes and life stages to study, as well as the main variables of the system. It includes de definition of the comparison unit for the system, which can include performance parameter as a functional unit, or only geometrical quantifiable parameter, as a declared unit, in case in which only some of the life cycle stages are considered. The scope also requires the definition of the transportation distances for material supply, and technologies involved. This allows the definition of the life-cycle inventory (LCI) for the main processes and upstream flows of the system, with data recollected by previous research or field recollection, defined as primary data; data included in public and private life-cycle databases such as the Federal LCA Commons® and Ecoinvent®, which was previously reported in environmental product declarations, are defined as secondary data.

Following the LCI, the life cycle impact assessment (LCIA) stage transforms the inventory into environmental impacts, which allows for stakeholder's interpretation and assessment in function of their perspective, providing a systemic perspective of environmental factors and inverted resources for one or more product systems. This last stage usually consists of 4 steps: classification, characterization, normalization, and weighting. Classification and characterization consist of grouping and pondering the resource consumption, emissions and wastes in quantifiable and meaningful environment and human impacts.

Normalization and weighting are considered optional steps, with the objective of present the characterized LCIA results to a common scale that is familiar and understandable to decision-makers, taking external references for comparison, or taking an internal reference for relative comparison. (Inti et al., 2016). Weighting in LCIA aspires at rating different impact categories against each other to determine their significance with respect to the context of conducting LCA, in accordance with stakeholder's perspectives and priorities. It is the nexus between the quantitative results of LCA and the values-based, subjective choices of decision makers. (Gloria et al., 2007).

LCA can also be coupled with life-cycle cost analysis (LCCA), allowing decision-makers to better ascertain the total impacts of a proposed project or policy, including new technologies. (Santero et al., 2011a, 2011b). It has become a staple in the development of economic policies for pavements, as evidenced by its adoption by the Federal Highway Administration and numerous state departments of transportation. (Corona et al., 2020).

2.3 Use of LCA methodology in paving industry

The application of the LCA tool to assess new technologies in infrastructure projects, such as new alternative materials is widely reported in the literature, allowing for a sustainability assessment and benchmarking (da Silva et al., 2021). In paving industry, the methodology is currently used to compare alternate design proposal by appraising the environmental impacts and costs, by life cycle stages and technologies applied, establishing a foundational framework for quantifying impacts and scope definition. Nonetheless, due to lack of functional unit standard definition, limited system boundaries, poor data quality and uncertainties, LCA results may fails to provide global conclusions on materials choice, management strategies and best practices policies. (Inti et al., 2016; Santero et al., 2011a).

In addition, most studies involving new methodologies have only focused their scope into the construction phase, while there are cases in which the environmental impact savings during the use phase may equal or even overpass the ones from the construction phase, while applying new technologies. (Araújo et al., 2014).

Knowing the current limitations of science in pavement LCA allow practitioners to incorporate the best available information, including best estimates and gross evaluations of uncertainties, contributing to transparency on pavement LCA framework and more focused research in order to fill gaps. (Santero et al., 2011b). These frameworks may help practitioners to better understand the implications of project-level decisions, perform what-if analysis to investigate trade-offs among alternatives, and achieve sustainability-related agency goals and objectives. (He et al., 2021). In this context, some LCA application on new materials in paving industry are as follow.

2.3.1 Temperature Reduction and Reclaimed Asphalt Pavements

One of the main objectives of new asphalt pavement research is to energy consumption, as well as demand of virgin raw materials. This has led to research on reducing the mixing and compaction temperature, and the use of waste materials such as Reclaimed Asphalt Pavement (RAP). The use of RCA and RAP in asphalt pavements has become a widespread practice in infrastructure technology, allowing for asphalt pavement to be considered 100% recyclable.

Aurangzeb et al (2014) performed a hybrid LCA was used to analyze the environmental footprint of using a reclaimed asphalt pavement (RAP) content in asphalt binder mixtures. The analysis took into consideration the material, construction, and maintenance and rehabilitation phases of the pavement life cycle. The results showed significant reductions in energy consumption and greenhouse gas (GHG) emissions with an increase in RAP content. (Aurangzeb et al., 2014).

Warm mix asphalt (WMA) with an addition of synthetic zeolites was compared with HMA and RAP asphalt mixes, using a comprehensive cradle to grave LCA, in which the environmental impacts associated with energy consumption and air emissions were assessed, as well as other environmental impacts resulting from the extraction and processing of minerals, binders and chemical additives; asphalt production; transportation of materials; asphalt paving; road traffic on the pavement; land use; dismantling of the pavement at the end-of-life and its landfill disposal or recycling. The results highlighted a potential technology combination of the WMA-zeolite mixes with RAP as a good alternative to HMA in environmental terms. (Vidal et al., 2013).

Comparison of these mixtures was also developed by Giani et al (2015), consisting of the analysis of life cycle of 1 km of road pavement and includes all stages of the life cycle: from extraction of virgin materials to end of life. Cold In-Place Recycling (CIR) was compared with traditional plant recycling at the end of life. Decrease in environmental impacts was found for the options that combine the use of RAP and WMA reaching up to a percentage of reduction of 12% for CO2eq, 15% for energy consumptions, 15% for water used during the lifecycle, and 10–15% for the three macro-categories of damage evaluated in the ReCiPe endpoint method. Additional reductions could be achieved by also applying CIR technology especially for greenhouse gas emissions (−9%). (Giani et al., 2015).

This trend also applies to other asphalt mixture variants. Warm Stone Mastic Asphalt (SMA) was compared to conventional SMA through an integrated life-cycle cost analysis (LCCA) and life-cycle assessment (LCA), to quantify the life-cycle economic and environmental potential impact. It proved that warm SMA is more environmentally friendly than conventional hot SMA, while it is economically competitive. (Leng et al., 2018a).

Santos et al (2018) performed a full process-based comparative life cycle assessment (LCA) looking at understanding the environmental impact of reducing mixing temperature, using warm mix technologies, namely chemical additives-based and foamed-based, and different rate of recycling (0% and 50% RAP). It also considered the combination of these technologies in subsequent life cycle stages as construction, maintenance, and rehabilitation of wearing courses of flexible pavements. Results showed a favorable environmental performance for foamed-based WMA mixture with a RAP content of 50%, employed in the wearing course throughout the pavement life cycle, in comparison with conventional solutions. (Santos et al., 2018).

Mascarenhas et al (2023) performed a cradle-to-gate LCA to compare the environmental performance of asphalt pavement in Brazil and Switzerland, using the practical rates of RAP use. The functional unit was defined based on the same traffic volume and service life of asphalt pavements, where the mix design and pavement structures follow the standards of the two countries. The results showed that RAP recycling can improve the environmental performance of hot asphalt mixtures in both countries, by reducing the binder amount. (Mascarenhas et al., 2023).

2.3.2 Crumb Rubber (CR) and Polymers

The use of crumb rubber and polymer has gained popularity in the evolution of paving industry, as it avoids other non-sustainable disposal method, such as landfilling and incineration. Comprehensive LCA studies performed on the conversion of waste vehicle tires into recycled crumb rubber (CR) granules as an alternative polymer for enhancing asphalt properties (Tushar et al., 2022). Farina et al (2017) performed a LCA of several types of road paving technologies based on the use of bituminous mixtures containing recycled materials such as crumb rubber from end-of-life tires and reclaimed asphalt pavement. Analyses were carried out by considering different scenarios which stem from the combination of production, construction, and maintenance operations, and by comparing them with a reference case involving use of standard paving materials. LCIA results in terms of gross energy requirement and global warming potential showed benefits in reducing up to 36% and 45% each respective indicator using the so-called wet technology of the rubberized bituminous mixtures. It was also enhanced by the use of RAP as partial aggregate substitution. (Farina et al., 2017).

Landi et al (2019) presented a comparative life cycle assessment (LCA) among three different typologies of hot mix asphalt mixtures (HMA): standard, cellulose-reinforced and ELT fiber-reinforced, with a functional unit of 1 m^2 and a temporal analysis of 30 years. The environmental impacts were quantified in terms of Cumulative Energy Demand (CED), Global Warming Potential (GWP), and ReCiPe midpoint and endpoint indicators. Considering such endpoint indicators, the ELT fiber-reinforced HMA resulted the best alternative (reduction of 25% in comparison with the standard HMA), followed by the cellulose-reinforced HMA (_10%), thanks to the higher service life. For some ReCiPe midpoint categories (Agricultural land occupation, Freshwater ecotoxicity, Freshwater eutrophication, Marine eutrophication and Terrestrial ecotoxicity), instead, the worst scenario is the cellulose HMA, due to the high contribution of the cellulose material. The implementation of textile fibers from ELT gives similar results, in comparison of traditional fibers (Landi et al., 2020; Martinez-Soto et al., 2022).

In combination with other alternative materials, studies have been developed with aims to compare the life cycle impacts of several pavement solution alternatives involving, in the binder and base layers, some eco-designed, hot- and cold-produced asphalt mixtures made up of recycled aggregates in substitution for natural filler and commercial recycled polymer pellets for dry mixture modification. Within the scope, asphalt pavement design criteria were applied and allowed for the functional unit definition in terms of mechanical performance and resilient modulus. LCIA results showed that the best performance was reached for the solutions involving a cold, in-place recycled mixture made up of RAP and jet grouting waste in the base layer, which lowered all the impact category indicators by 31% on average compared to those of the traditional pavement solution. (Oreto et al., 2021).

2.3.3 Plastic Recyclates or Recycle Plastic Pellets

Life cycle assessment of asphalt pavement with addition of plastic recyclates or Recycle Plastic Pellets (RPP) have shown to be environmentally advantageous in comparison to its conventional counterpart. Its inclusion as an Asphalt modifier or as a synthetic aggregate replacement in asphalt mixes has been successfully covered in case studies, with the use of primary data from recycling facilities and sensitivity analyses for type of plastic recyclate and mix percentage. Santos et al, (2021) investigated the processes that lead to the conversion of waste plastics into recycled plastic pellets to be used either as an additive (wet method) or as a replacement of natural aggregate (dry method) in the production of asphalt mixes, through a comparative LCA. Among its results, it evidences environmental advantages for the use of soft recycled plastic as polymer for Asphalt modification in comparison with its conventional virgin counterpart. Using such “wet” method, it results in asphalt pavement emission’s reduction of up to 10.2% of CO_2-eq in replacement of 8% virgin polyethylene with the same amount of RPP. Through the “dry” method, the environmental savings were not as evident, considering that recycling costs of RPP could potentially be much higher than that of natural aggregates. (Santos et al., 2021).

Rangelov et al (2021) performed a cradle-to-gate and a cradle-to-grave LCA of asphalt pavement with recycled post-consumer polyethylene (RP), in which a variety asphalt pavement sections, produced with RP, were designed, and compared to its conventional HMA and polymer-modified asphalt. The RP mixtures were made with recycled polyethylene pellets introduce via a dry process and evaluated through the “Tool for Reduction and Assessment of Chemical and other Environmental Impacts” (TRACI) as the impact assessment method, demonstrating that RP pavements are environmentally beneficial relative to HMA when savings in pavement thickness of 12.5% or extension of maintenance cycles by 7% are achieved. In relation to polymer-modified alternative, RP sections presents environmental benefits when equal performance is achieved with no changes in thickness or maintenance (Rangelov et al., 2021).

2.4 Use of RPET in Hot Mix Asphalt Pavements

In the present study, particular attention will be given to the use of post-consumer polyethylene terephthalate (RPET) as an alternative material for asphalt pavements. With this context, the following relevant studies are presented.

2.4.1 The feasibility of recycled micro polyethylene terephthalate (PET) replacing natural sand in hot-mix asphalt – Ferreira et al (2022)

Ferreira et al, (2022) studied the potential of recycled micro-PET (mPET) replacing natural sand on hot-mix asphalt (HMA) mechanical behavior by weight and volume. They used a penetration grade 50/70 asphalt binder, and local sources of the Federal District/Brazil provided the coarse aggregates, presenting mineralogical origin from limestone rock. The fine aggregates used were stone dust from a limestone source, natural sand, and polyethylene terephthalate micronized as powder, resulting from the recycling process of consumer water bottles.

According to the RPET supplier description, the recycling process consisted in collecting and cleaning the PET bottles and removing stickers, caps, and cap rings. Then, the PET was crushed into different blades and milled until micronization led to the particles' size allowing passage through 0.42 mm sieve mesh.

They demonstrated the contribution of the RPET in enhancing the resistance to moisture damage, especially for regions where the pavement deterioration process is associated with an intensive rainfall regime, thus demonstrating this application's practical feasibility in concrete asphalt paving.

Data corresponding to characterization of the asphalt binder and properties of aggregates used during the work is presented in Table 1 and Table 2. (Ferreira et al., 2022)

Table 1. Characterization of asphalt binder as reported in Ferreira et al, (2022).

Property	**Standard Method ASTM/Brazilian**	**Result**	**Brazilian Specification**
Specific Gravity	D 70/DNER ME 193	1.003	
Penetration (10^{-1} mm)	D5/DNIT 155	51	50 to 70
Softening Point (°C)	D 36/DNIT 131	47.5	≥46
Flash Point (°C)	D 92/NBR 11,341	323	>235
Brookfield Viscosity 135 °C	D 4402/NBR 15,184	351	>274
Brookfield Viscosity 150 °C	D 4402/NBR 15,184	184	>112
Brookfield Viscosity 177 °C	D 2872/NBR 15,235	71	57 to 285
RTFOT—% Weight Range	D 2872/NBR 15,235	-0.29	-0.50 to 0.50
RTFOT—Residual Penetration (%)	D 5/DNIT 155	61.7	55
RTFOT—Softening Point Increase (°C)	D 36/DNIT 131	3.4	<8

Table 2. Properties of aggregates for HMA designs, as reported in Ferreira et al, (2022).

Property	**Standard Method ASTM/Brazilian**	**Coarse Aggr.**	**Natural Sand**	**Rock Filler**	**RPET**	**Brazilian Specification**
Bulk Specific Gravity	ASTM C 127/DNIT 413	2.703	-	-	-	-
Apparent Specific Gravity	ASTM C 127/DNIT 411	2.751	2.655	2.835	1.41	-
Los Angeles Abrasion (%)	ASTM C 131/DNER 035	15	-	-	-	< 40
Shape Index	DNIT 424	0.9	-	-	-	> 0.5
Fine Aggregate angularity	ASTM C1252/DNIT 415		55/56	-	-	> 45
Flat and elongated part. (5:1)	ASTM D4791/DNIT 429	3.6	-	-	-	< 10
Sand Equivalent (%)	ASTM D 2419/DNER 054	-	74	86	-	> 55
Absorption	ASTM C 127/DNIT 413	0.65	-	-	-	-

2.4.2 Mechanical behavior of asphalt concrete with insertion of PET flakes – Arao et al, (2017)

Arao et al, (2017) assessed the technical viability of inserting recycled ground PET in asphalt concrete. PET flakes of different sizes were inserted in varied ratios, and there was a partial replacement of fine aggregate with PET micronized. They used a penetration grade 30/45 asphalt binder, and natural granitic aggregates from the state of Rio de Janeiro. See Figure 3.

RPET flakes were processed directly in lab with grinding equipment and sieved until a nominal size of 2 mm and 10 mm. Micronized RPET was commercially available and was used as filler replacement. The results of the mechanical tests were better for the mixtures with PET addition.

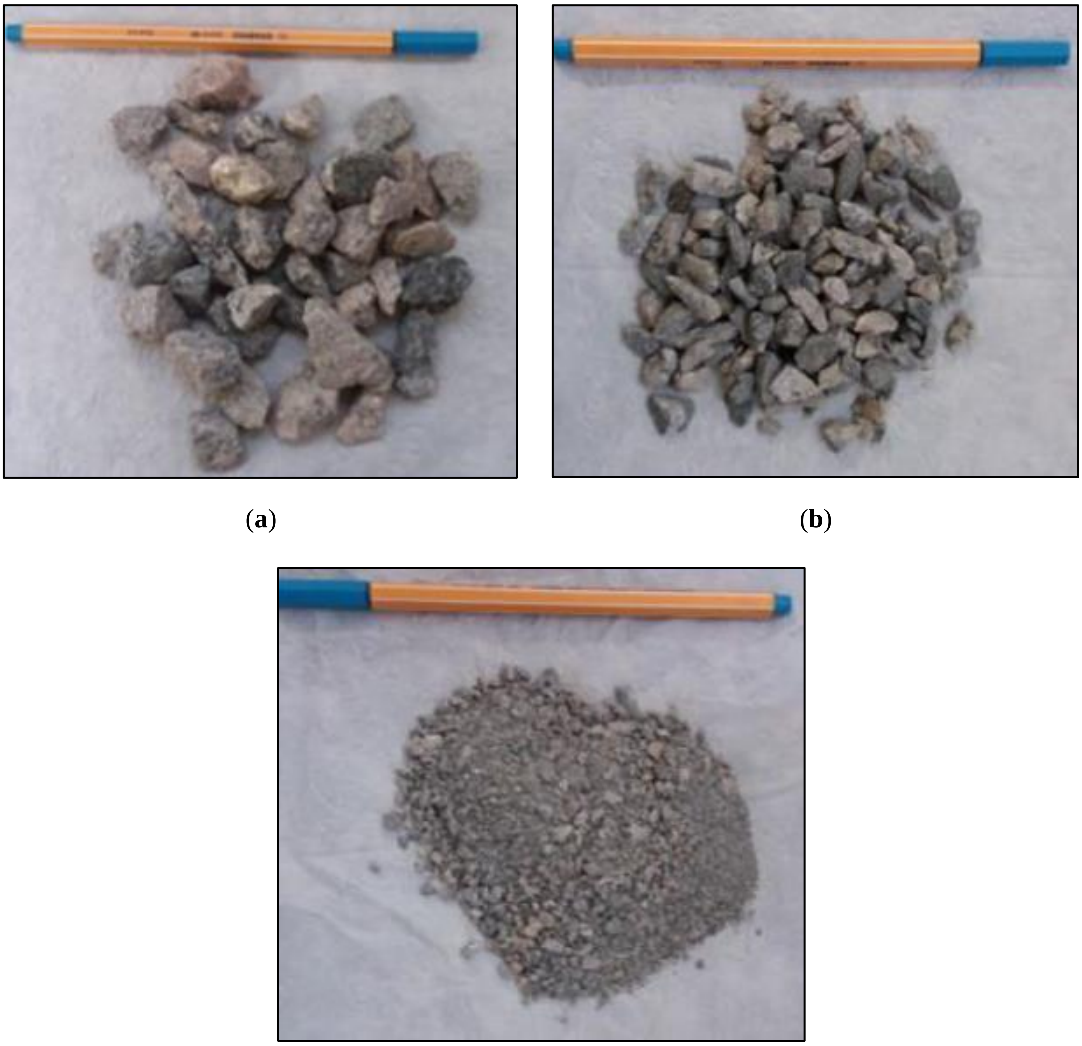
Data corresponding to characterization of the asphalt binder and properties of aggregates used during the work is presented in Table 3 and Table 4. (Arao et al., 2017)

Table 3. Characterization of asphalt binder as reported in Arao et al, (2017)

Property	**Standard Method ASTM/Brazilian**	**Result**	**Brazilian Specification**
Specific Gravity	D 70/DNER ME 193	1.01	
Penetration (10^{-1} mm)	D5/DNIT 155	36	30 to 45
Softening Point (°C)	D 36/DNIT 131	52	≥52
Flash Point (°C)	D 92/NBR 11,341	348	>235
Brookfield Viscosity 135 °C	D 4402/NBR 15,184	472.5	>374
Brookfield Viscosity 150 °C	D 4402/NBR 15,184	227	>203
Brookfield Viscosity 177 °C	D 2872/NBR 15,235	81.5	76 to 285
RTFOT—% Weight Range	D 2872/NBR 15,235	−0.09	<0.5
RTFOT—Residual Penetration (%)	D 5/DNIT 155	69	>60
RTFOT—Softening Point Increase (°C)	D 36/DNIT 131	4	<8

Table 4. Properties of aggregates for HMA designs, as reported in Arao et al, (2017)

Property	**Standard Method ASTM/Brazilian**	**Gravel 1**	**Gravel 0**	**Rock Filler**	**Brazilian Specification**
Bulk Specific Gravity	ASTM C 127/DNIT 313	2.7	2.8	2.74	-
Apparent Specific Gravity	ASTM C 127/DNIT 411	2.6	2.1	-	-
Los Angeles Abrasion (%)	ASTM C 131/DNER 035	23	35		< 40
Sand Equivalent (%)	ASTM D 2419/DNER 054	-	-	78	> 35
Absorption	ASTM C 127/DNIT 413	0.75	0.80		



(**a**) (**b**)

(**c**)

Figure 3. Aggregates used for sustainable pavement with RPET: (a) gravel 1; (b) gravel 0; (c) rock filler.

It was defined that higher increase in the resistance parameters and life cycle was in the mixture with 0.5% of 10 mm PET flakes and replacement of 2.5% of the fine aggregate with PET powder. Therefore, setting the use of ground PET bottles in asphalt concrete as a technically and environmentally viable option.

2.4.3 Evaluation of resilient behavior of a clayey soil with polyethylene terephthalate (PET) insertion for application in pavements base – Carvalho et al, (2019)

Carvalho et al, (2019) proposed the use of RPET flakes as an alternative material for pavements base. They added the flakes into a clayey soil classified as laterite, typically found in large regions of Brazil. See Figure 4. It was mixes with a dry weight percentage of 3, 5 and 7%, and their mechanical parameters were explored.

Figure 4: Lateritic soil and RPET used in the study. Extracted from Carvalho et al, (2019).

The results indicated that the insertion of PET influences the mechanical behavior of the soil. It was found that resilient modulus increases, with respect to that of pure soil, for mixtures with the lowest content of PET (3%). For tests with higher contents of PET flakes, the Resilient Modulus decreases. This research concluded that the clayey soil mixed with PET flakes can be used as an alternative material for pavements base if a low content of flakes is used. (Carvalho et al., 2019).

3 LCA METHODOLOGY

The structure of a life cycle assessment consists of the scope definition, inventory analysis, and impact assessment for each flow, as defined in the methodology framework of the standards ISO 14040 (2006) and ISO 14044 (2006). It follows an iterative interpretation step until it fulfills the goals defined in the scope.

3.1 Goal and Scope Definition

3.1.1 Product System and Boundaries

The main goal of this study is a case comparison of the environmental performance and impacts of a conventional HMA pavement and an HMA pavement with the addition of RPET in flake and micronized form, added in dry conditions as a natural aggregate replacement, in support of previous research that highlighted the potential of its inclusion to improve the mechanical parameters, superior aging and moisture damage resistance, and asphalt–aggregate adhesion, thus promoting an alternative-sustainable pavement project variant.

The spatial system boundary is the city of Brasilia, Federal District, Brazil, following the same spatial setting of the sustainable pavement alternatives studied. The life cycle boundary begins with the main materials extraction (cradle) and recollection and ends with the pavement construction (built). Due to the lack of studies on the operation phase of such new sustainable pavement proposals, the following stages will not be considered in the LCA scope: maintenance, use performance, pavement wearing, demolition, or reclamation. Figure 5 presents the product system for the pavement variants, defining the main processes considered for the cradle-to-built LCA.

The processes are composed of primary data, obtained for the HMA mixture proportions from the works of Ferreira et al, (2022) and Arao et al, (2017) for each surface course and the natural soil improvement with RPET as a base course for pavement structure design. The extraction and upstream production, as well as the transport-related input and output, are composed of secondary data. The transportation distances were determined as an average for material supply for the product system, considering the manufacturing of graduated gravel for base and subbase and the HMA production in the same facility. The energy supply is adapted from the energy matrix supply of Brazil (EPE, 2020), coupled with the upstream secondary data corresponding to each type of energy production facility.

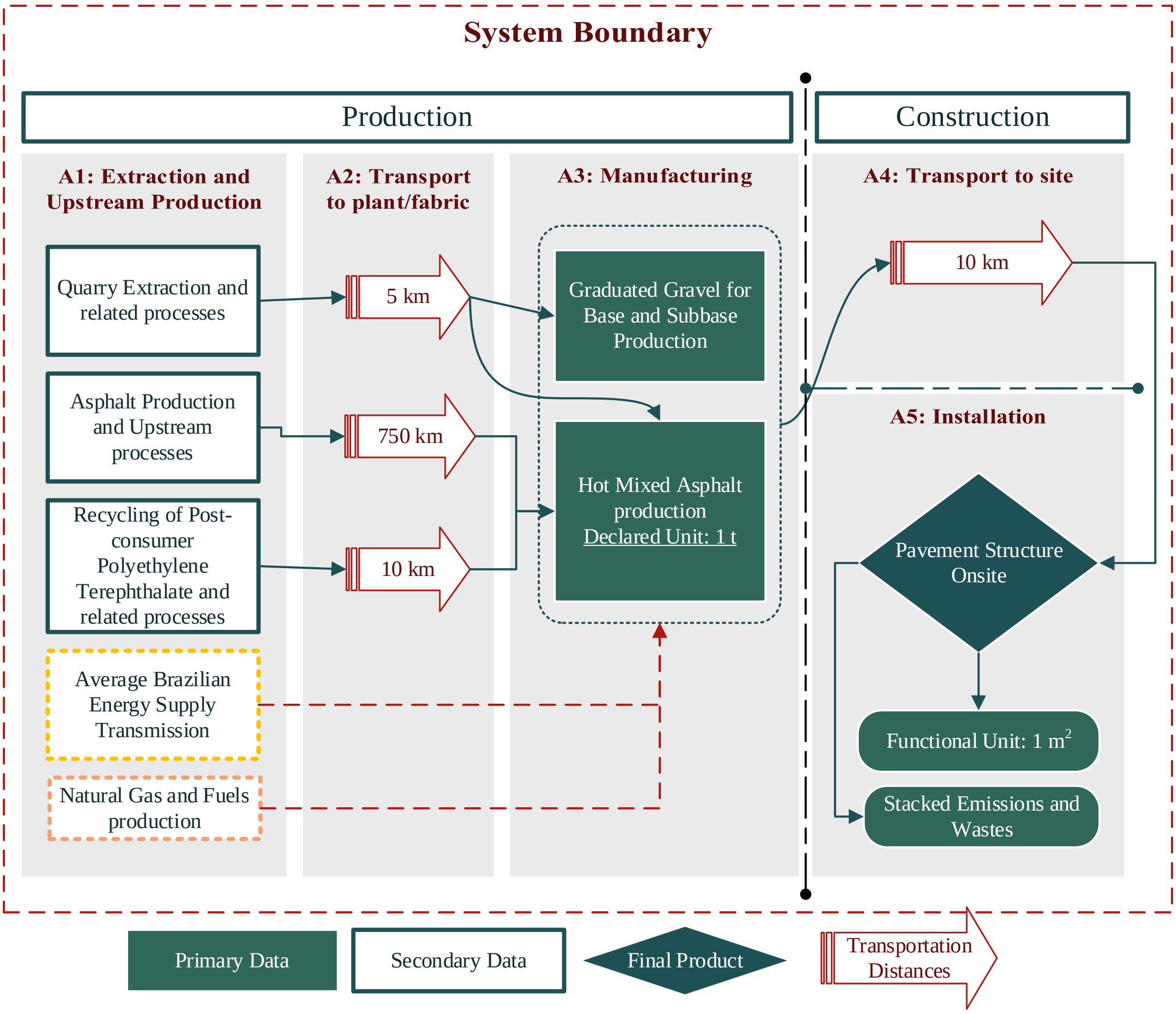


Figure 5: Product system and system boundary.

The stablished product system allows for the following LCA comparison points.

- Declared unit (DU) comparison. For this study, a DU of 1 metric ton of HMA mixtures is defined for each author, following it mix design and materials, detailed in Table 5.

Table 5: Declared Unit Nomenclature and Definition

Ref.	ID	Definition	Description
Ferreira et al, (2022)	M1.0	HMA - C1	Conventional HMA 1
	M1.1	HMA - 2mPET	2% addition of RPET micronized
	M1.2	HMA - 8mPET	8% addition of RPET micronized
Arao et al, (2017)	M2.0	HMA - C2	Conventional HMA 2
	M2.1	HMA - 0.5fPET_2mm	0.5% addition of 2mm RPET flakes
	M2.2	HMA - 1.0fPET_2mm	1% addition of 2mm RPET flakes
	M2.3	HMA - 0.5fPET_10mm	0.5% addition of 10mm RPET flakes
	M2.4	HMA - 1.0fPET_10mm	1% addition of 10mm RPET flakes
	M2.5	HMA - 0.5fPET_10mm+2.5mPET	0.5% addition of 10mm RPET flakes and 2.5% RPET micronized

- Functional unit (FU) comparison. For this study, a FU of 1 m^2 is defined for each case, following HMA mixtures and pavement infrastructure combination. The FU's nomenclature is detailed in Table 6.

Table 6: Functional Unit Nomenclature and Definition

Ref.	DU	ID	Definition	Surface Course	Base Course	Subbase Course	Subgrade
Ferreira et al, (2022)	M1.0	1.0.1	M1.0 - BG C5	HMA - C1	BG - C5*	BG - C1*	SP CEUnB**
		1.0.2	M1.0 - S97T03		S97T03	BG - C1*	
	M1.1	1.1.1	M1.1 - BG C5 - SS	HMA - 2mPET	BG - C5*	N.A.	
		1.1.2	M1.1 - BG C5				
		1.1.3	M1.1 - S90P10		S90P10	BG - C1*	
		1.1.4	M1.1 - S97T03		S97T03		
	M1.2	1.2.1	M1.2 - BG C5 - SS	HMA - 8mPET	BG - C5*	N.A.	
		1.2.2	M1.2 - BG C5				
		1.2.3	M1.2 - S90P10		S90P10	BG - C1*	
		1.2.4	M1.2 - S97T03		S97T03		
Arao et al, (2016)	M2.0	2.0.1	M2.0 - BG C5	HMA - C2	BG - C5*	BG - C1*	
	M2.1	2.1.1	M2.1 - BG C5	HMA - 0.5fPET_2mm	BG - C5*	BG - C1*	
	M2.2	2.2.1	M2.2 - BG C5	HMA - 1.0fPET_2mm	BG - C5*	BG - C1*	
		2.2.2	M2.2 - S90P10		S90P10		
		2.2.3	M2.2 - S97T03		S97T03		
	M2.3	2.3.1	M2.3 - BG C5 - SS	HMA - 0.5fPET_10mm	BG - C5*	N.A.	
		2.3.2	M2.3 - S90P10 - SS		S90P10	N.A.	
		2.3.3	M2.3 - S90P10		S90P10	BG - C1*	
		2.3.4	M2.3 - S97T03 - SS		S97T03	N.A.	
		2.3.5	M2.3 - S97T03		S97T03	BG - C1*	
	M2.4	2.4.1	M2.4 - BG C5 - SS	HMA - 1.0fPET_10mm	BG - C5*	N.A.	
		2.4.2	M2.4 - S90P10 - SS		S90P10	N.A.	
		2.4.3	M2.4 - S90P10		S90P10	BG - C1*	
		2.4.4	M2.4 - S97T03 - SS		S97T03	N.A.	
		2.4.5	M2.4 - S97T03		S97T03	BG - C1*	
	M2.5	2.5.1	M2.5 - BG C5 - SS	HMA - 0.5fPET_10mm+2.5 mPET	BG - C5*	N.A.	
		2.5.2	M2.5 - BG C5				
		2.5.3	M2.5 - S90P10		S90P10	BG - C1*	
		2.5.4	M2.5 - S97T03		S97T03		

*Taken from Internal MeDiNa databases for calibrated pavement structure materials. **Taken from (Carvalho et al., 2019) for tropical typical soil of Brasilia, D.F.

3.1.2 Products and Materials

This section details the main products and materials considered in the product system.

3.1.2.1 Recycled Post-consumer Polyethylene Terephthalate (RPET)

RPET is a waste management process product of post-consumer polyethylene terephthalate, which underwent a secondary recycling procedure involving mechanical procedures such as cutting/shredding, milling, or grinding. The formats used for the present pavement variants consist of flake form, with a nominal size of 10 mm, and micronized form, with a nominal size of 0.42 mm. A combination of these two RPET formats were added to the HMA mixes in mass percentage substitution of the rock filler. Illustration of the RPET’s flake form and micronized form is presented in Figure 6. The addition of the RPET into the HMA mixes follows the “dry” procedure, in which the plastic is added in the final segment of the mixing process and after introducing and incorporating the asphalt binder with the aggregate (Ben Zair et al., 2021).

(**a**) (**b**)

Figure 6: RPET format for use in pavement variants: (a) flake form of 10 mm nominal size; (b) micronized form of 0.42 mm nominal size.

For the present study, a cut-off rule is applied for the previous life cycle of RPET. This considers only the steps of production of RPET, which can be numbered as: (a) recovery: collection of postconsumer plastic; (b) sorting and separation: sorting of plastics from other collected recovered materials and separating mixed plastics into in-dividual resins; and (c) reclaimer operations: with additional separation and processing of postconsumer resin by a reclaimer to convert the received material into clean resin ready for use in manufacturing. The material is considered “on demand” during all HMA production, and a freightage distance of 10 km was stablished for the present LCA.

3.1.2.2 Asphalt Binder

The asphalt binder used on the HMA designs is a petroleum asphalt cement (PAC) 30/45 and 50/70 commonly used in Brazilian road paving. The characterization of the asphalt binder is presented in was presented for each author in Tables 1 and 3. The material is considered “on demand” during all HMA production, and a land freightage distance of 750 km was stablished for the present LCA, considering the closest petroleum refinery to Brasília, D.F., located in the city of Belo Horizonte, state of Minas Gerais.

3.1.2.3 Aggregates

The aggregates used for the HMA design are from granitic and limestone origin. The properties of these aggregates for each are presented in Tables 2 and 4.

The aggregates used for the pavement’s base and subbase course consist of generic graduated material of gneiss matrix origin and are considered for the functional unit assessment with the pavement structure design methodology.

The aggregates are considered “on demand” during all HMA production, and a land freightage distance of 5 km was established for the present LCA, from the aggregate deposit to production plant or project site.

3.1.2.4 Linear diagram of occurrences

The linear diagram of occurrences is proposed and presented in Figure 7, with hypothetical transport distances to stablish the spatial boundary of the LCA. It takes as the central point the HMA production plant, and considers an average transport distance for the project site of 10 Km for delivery of the HMA mixtures.

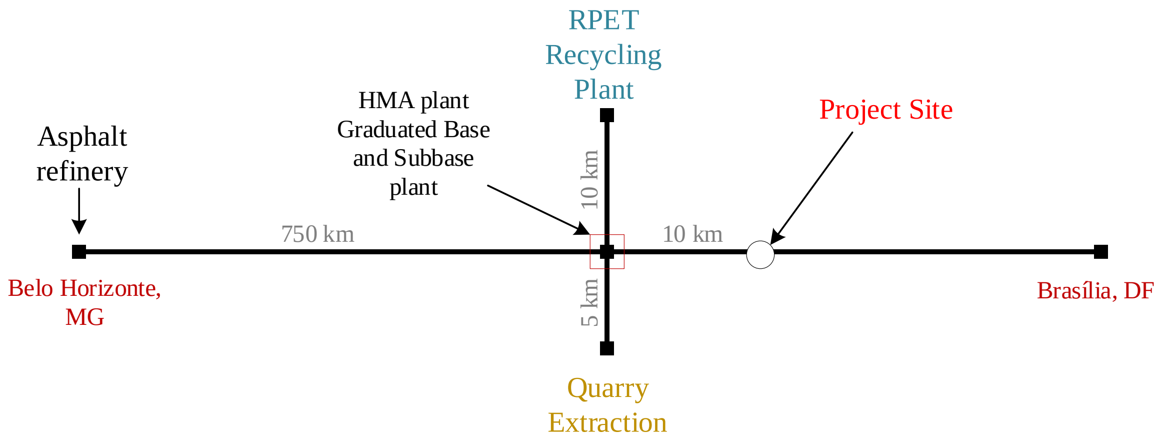


Figure 7: Linear diagram of occurrences for hypothetical transport distances

3.1.3 Declared Units

The production of one ton of conventional HMA and one ton of HMA production with RPET addition as corresponding declared units is defined as a first comparative point to assess the inventory and environmental impacts of the analogical production for each mix in the same hypothetical production plant. Such comparison only contemplates the material quantities according to the mix design proposed by the authors, and due to the "dry" process inclusion of the RPET into the mix, the present LCA will not consider having any significant variation of energy or resource consumption for the sustainable mixes. Figure 8 and Figure 9 details the mechanical characterization and dosage for the HMA with the optimal Asphalt content reported respectively, highlighting the performance improvements of the mix with the inclusion of the RPET, such as an increase on the resilient modulus and tensile strength, as well as a decrease in the bulk specific gravity and void volume percentage.

The dosage of hot mix asphalt in the percentage of the total mass is presented in Figure 10.

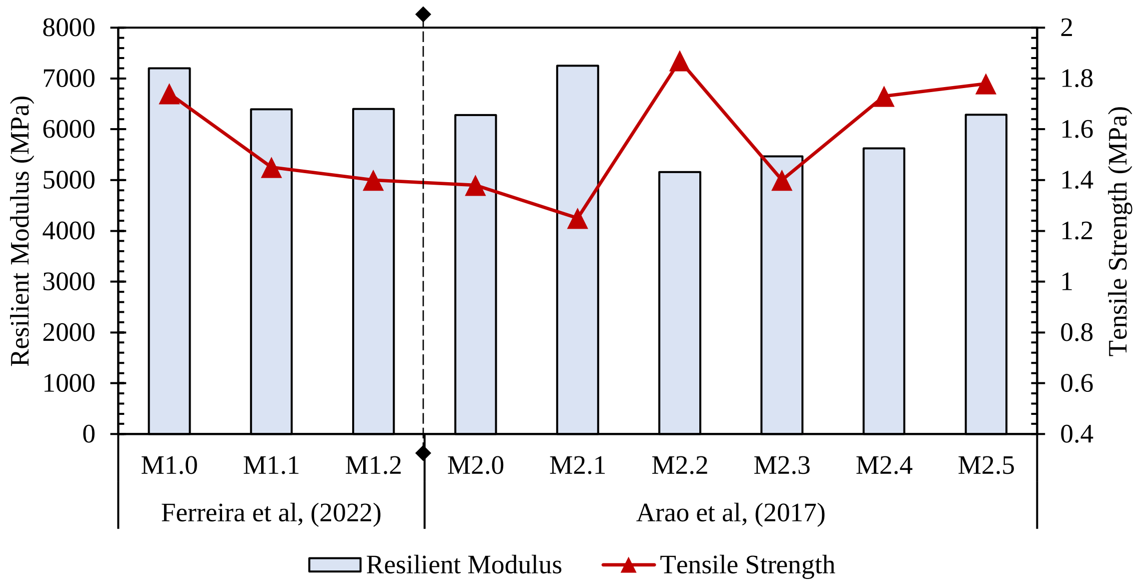


Figure 8: Declared Units mechanical characterization: Resilient Modulus and Tensile Strength for each HMA mixes.

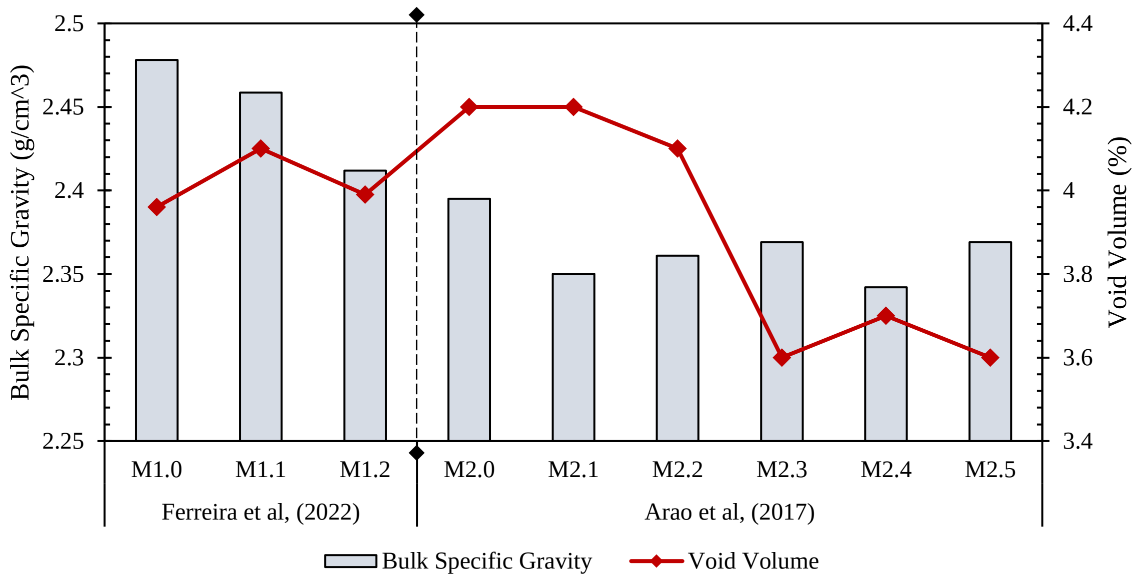
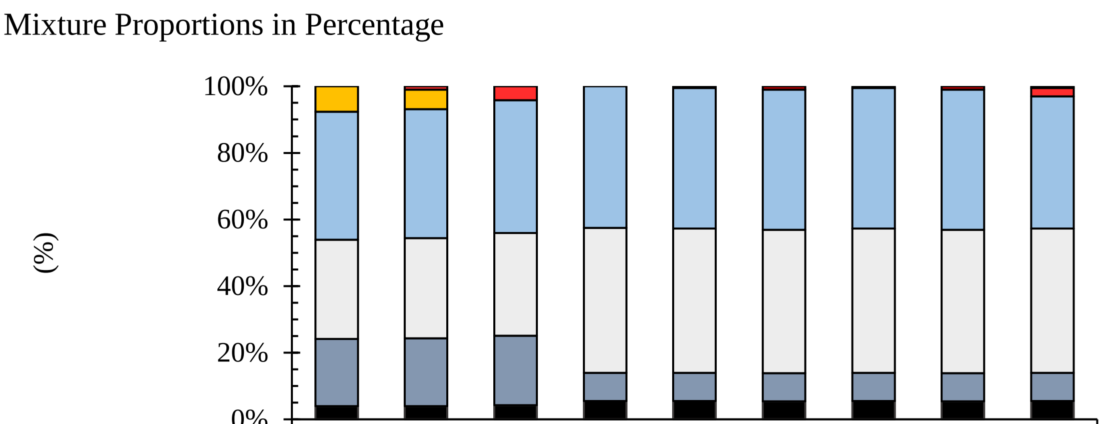


Figure 9: Declared Units volumetric characterization: Bulk Specific Gravity and Void Volume for each HMA mixes.



	M1.0	M1.1	M1.2	M2.0	M2.1	M2.2	M2.3	M2.4	M2.5
RPET - Flakes					0.5	1	0.5	1	0.5
RPET - micronized		1.1	4.2374						2.5
Natural Sand	8.0	6.0							
Filler	40.0	40.0	40	42.5	42.3	42.1	42.3	42.1	39.8
Gravel 0	31.0	31.0	31	43.5	43.3	43	43.3	43	43.3
Gravel 1	21.0	21.0	21	8.5	8.5	8.4	8.5	8.4	8.5
PAC 50/70	4.1	4.1	4.25	5.5	5.5	5.4	5.5	5.4	5.5

Figure 10: Declared Units dosage description for each HMA mixes in percentage of total mass.

3.1.4 Functional Units

As a second comparative point, we define one square meter of pavements for each mix as functional units, taking into consideration the mechanical and performance parameters under the National Design Methodology (MeDiNa) (IPR and COPPE, 2020), a Brazilian methodology. It implements a mechanistic–empiric pavement design methodology and validation based on elastic multi-layer analysis. The main parameters consist of the resilience modulus and fatigue curve assessment.

3.1.4.1 Design Algorithm and considerations

For the functional unit's structure definition was applied the following design algorithm under the MeDiNa criteria.

The first step consisted of the summary of the mechanical parameters and characterization for the HMA mixtures and base and subbase course materials. For the HMA mixtures, the main parameters were the resilient modulus, volumetric and fatigue parameters. Then the MeDiNa algorithm incorporates the resilient modulus with the mixture fatigue factor, which is defined as the integration of the fatigue curve function with the tensile deformation limits of 100 μm and 250 μm. It allows for the assignation of fatigue classes for each asphalt mixtures that represents the overall pavement performance under the framework stablished by MeDiNa. With a higher fatigue class, the better pavement performance. In Table 7 are presented the mechanical and volumetric parameters, as well of the fatigue class for each HMA mixture.

Table 7: HMA mixtures mechanical and volumetric parameters

Author	Ferreira et al, (2022)			Arao et al, (2017)					
ID	M1.0	M1.1	M1.2	M2.0	M2.1	M2.2	M2.3	M2.4	M2.5
Poisson Coef.	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Constituent Model	linear								
Resilient Modulus	7200	6390	6400	6278	7251	5160	5466	5624	6289
Asphalt	CAP 50/70			CAP 30/45 + 1% DOPE					
Bulk Specific Gravity	2.478	2.459	2.412	2.395	2.35	2.361	2.369	2.342	2.369
Tensile Strength	1.74	1.45	1.4	1.38	1.25	1.87	1.4	1.73	1.78
Asphalt Percentage	4.1	4.1	4.25	5.5	5.5	5.4	5.5	5.4	5.5
Void Volume	3.96	4.1	3.99	4.2	4.2	4.1	3.6	3.7	3.6
Gradation	C								
Los Angeles Abrasion (%)	15	15	15	35	35	35	35	35	35
Norm	DNIT 031/2006								
Fatigue | k1	8E-11	7.00E-09	7.00E-09	8E-11	4.00E-11	2.00E-07	5.00E-07	5.00E-06	7.00E-09
Fatigue | k2	-3.112	-2.803	-2.803	-3.112	-3.142	-2.408	-2.413	-2.121	-2.803
N100	2.24E+02	1.14E+03	1.14E+03	2.24E+02	1.48E+02	8.57E+02	2.24E+03	1.52E+03	1.14E+03
N200	1.30E+01	8.74E+01	8.74E+01	1.30E+01	8.31E+00	9.44E+01	2.46E+02	2.18E+02	8.74E+01
FFM	0.69	1.00	1.00	0.69	0.62	0.98	1.15	1.10	1.00
Fatigue Class	Class 0	Class 3	Class 3	Class 0	Class 0	Class 2	Class 4	Class 3	Class 3

For the base, subbase and subgrade course materials, the MeDiNa considers the materials under the granular tab, represented by its resilient modulus, Poisson coefficient and permanent deformation parameters. The software also allows for a non-linear analysis of the resilient modulus model, obtained through the essay method DNIT 134/2018-ME. For the permanent deformation parameters, the essay method applied is the DNIT 179/2018-IE, following the model from (Guimarães, 2009). The material's mechanical and volumetric parameters are presented in Table 8.

For the second step, the traffic condition was defined for the design methodology and consisted of an equivalent standard axes load (ESAL) equal to 5×10^5 eq. axes a year, with a 10-year analysis period. Such traffic is representative of a medium-traffic primary arterial road system, with a reliability requirement of 95%.

Table 8: Base, subbase, and subgrade course material's mechanical and volumetric parameters

Parameters		BG Gneiss C5	BG Gneiss C1	S90P10	S97T03	SP CEUnB
Poisson Coefficient		0.35	0.35	0.35	0.35	0.3
Constituent Model		Linear	Linear	Non-linear	Non-linear	Non-linear
Resilient Modulus		381	259	N.A.	N.A.	N.A.
Non-Linear 'RM' Parameters	k1	N.A.	N.A.	385.44	235.89	244
	k2	N.A.	N.A.	0.228	-0.105	0.1
	k3	N.A.	N.A.	0.031	0.411	0.263
	k4	N.A.	N.A.	0	0	0
Description		Graduated gravel	Graduated gravel	CEUnB soil + 10 % RPET micronized	CEUnB soil + 3 % RPET Flakes	Natural typical Soil of Brasilia
MCT group		N.A.	N.A.	N.A.	N.A.	LG'
MCT - c'		N.A.	N.A.	N.A.	N.A.	1.92
MCT - e'		N.A.	N.A.	N.A.	N.A.	0.89
Specific Mass (g/cm^3)		2.223	2.268	1.61	1.681	1.7125
Optimal Water Content (%)		5	5.8	19.4	20	19.8
Compaction Energy		Modified	Modified	Intermediate	Intermediate	Intermediate
Los Angeles Abrasion (%)		43	41	N.A.	N.A.	N.A.
Norm or Specification		DNIT ES 141	DNIT ES 141	N.A.	N.A.	N.A.
Permanent Deformation	k1	0.0868	0.1608	0.206	0.206	0.206
	k2	-0.2801	-0.097	-0.24	-0.24	-0.24
	k3	0.8929	0.525	1.34	1.34	1.34
	k4	0.0961	0.0752	0.038	0.038	0.038

As a last step, with all the materials and traffic conditions inserted in the project on the MeDiNa software, the pavement structure is proposed, maintaining the subbase and base course thickness constant, and evaluating the thickness of the surface course. For the HMA mixes with better performance, in some combinations, the minimum thickness of 5 cm was obtained, proceeding with the optimization of the subsequent base course thickness. The pavement structure that passed the reliability criteria was printed with a summary of all input data, together with the cracked area and rutting results. Software results of MeDiNa for the functional units are annexed in supplementary material. In Figure 11 is represented the Functional Unit for all pavement structure proposal considered during the MeDiNa analysis.

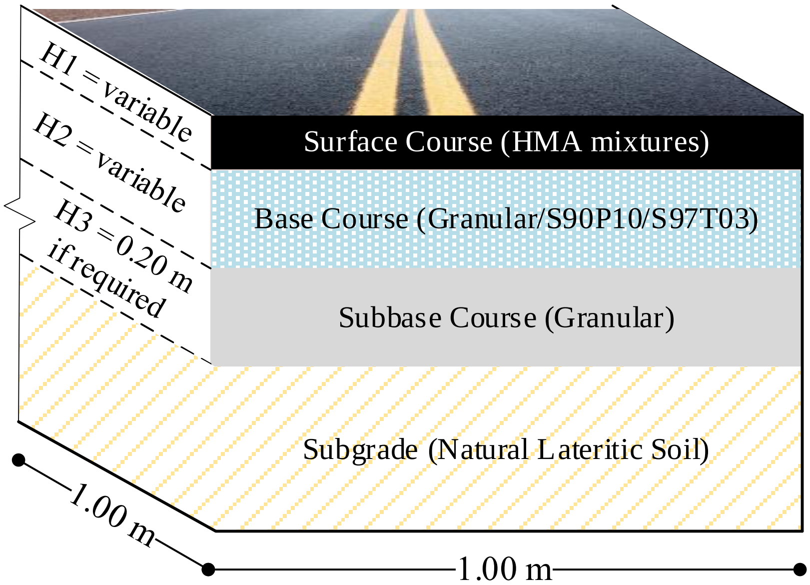


Figure 11: Functional Unit Representation with each pavement layer and physical dimension

3.1.4.2 Project Results and Structure

For the present study, the pavement structures were proposed in combination with the DU defined for each author, base and subbase course, and subgrade course from natural typical soil of Brasília, D.F. The combinations are presented in Figure 12 and Figure 13, corresponding for each author's DU, together with performance results.

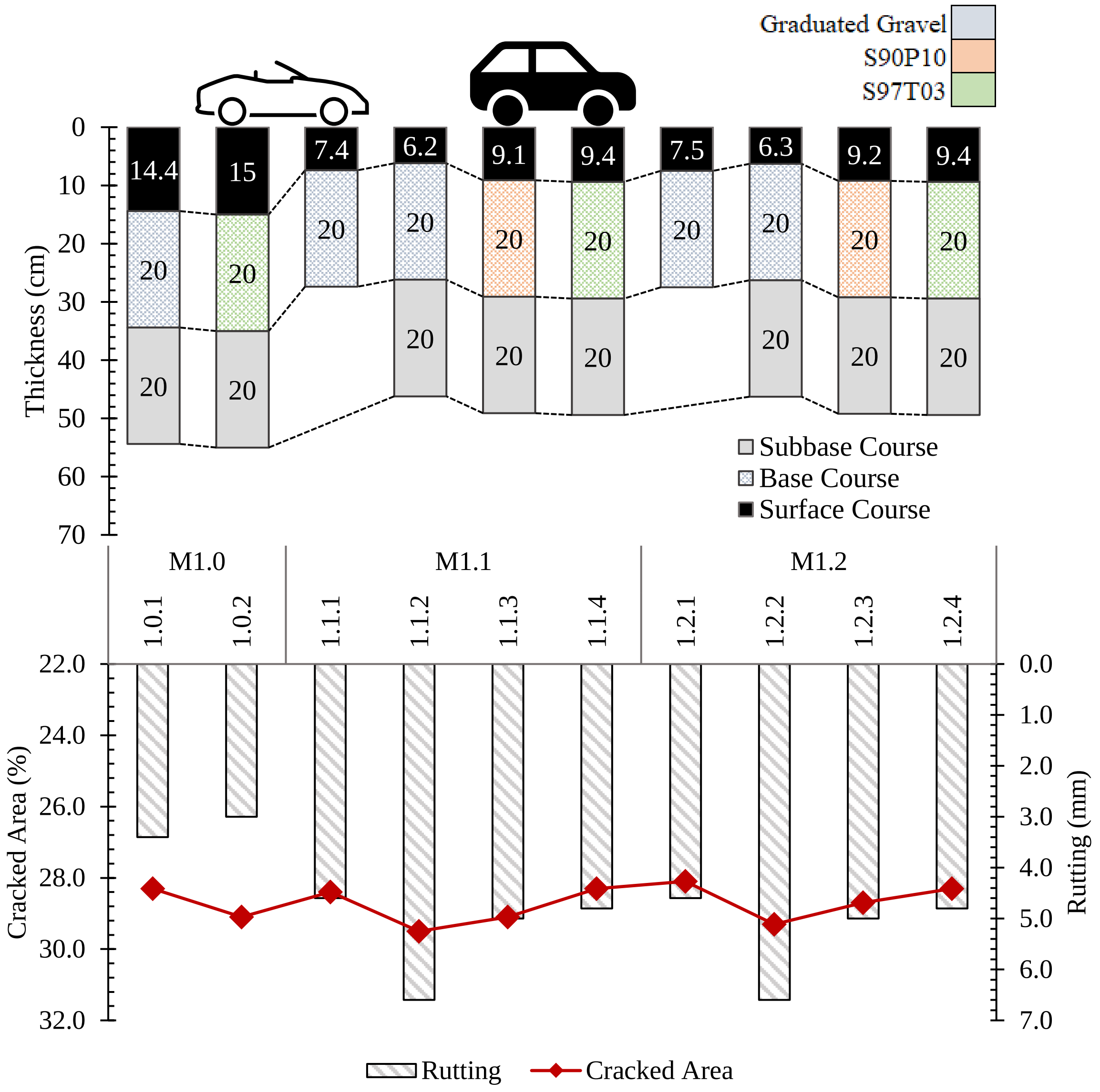


Figure 12: Functional unit characterization Part 1, with thickness for each pavement variant and functional parameters such as cracked area (%) and track sinking prediction (mm) by the end of the analysis period.

For the pavement structures with the HMA mixtures reported by Ferreira et al, (2022), a tendency of surface course thickness reduction was reached by the software MeDiNa, decreasing from 14.4 cm to 6.2 cm with the use of the M1.1 mix and 6.3 cm with the M1.2 mix, combined with a graduated gravel base and subbase course. Less significant decrease was also achieved using the alternative base course with natural Brazilian soil improved with RPET. Alternative FU variants were proposed without the use of a subbase course, as the software MeDiNa allowed for testing, resulting in an overall slender pavement structure. Rutting and cracked area results are considered acceptable.

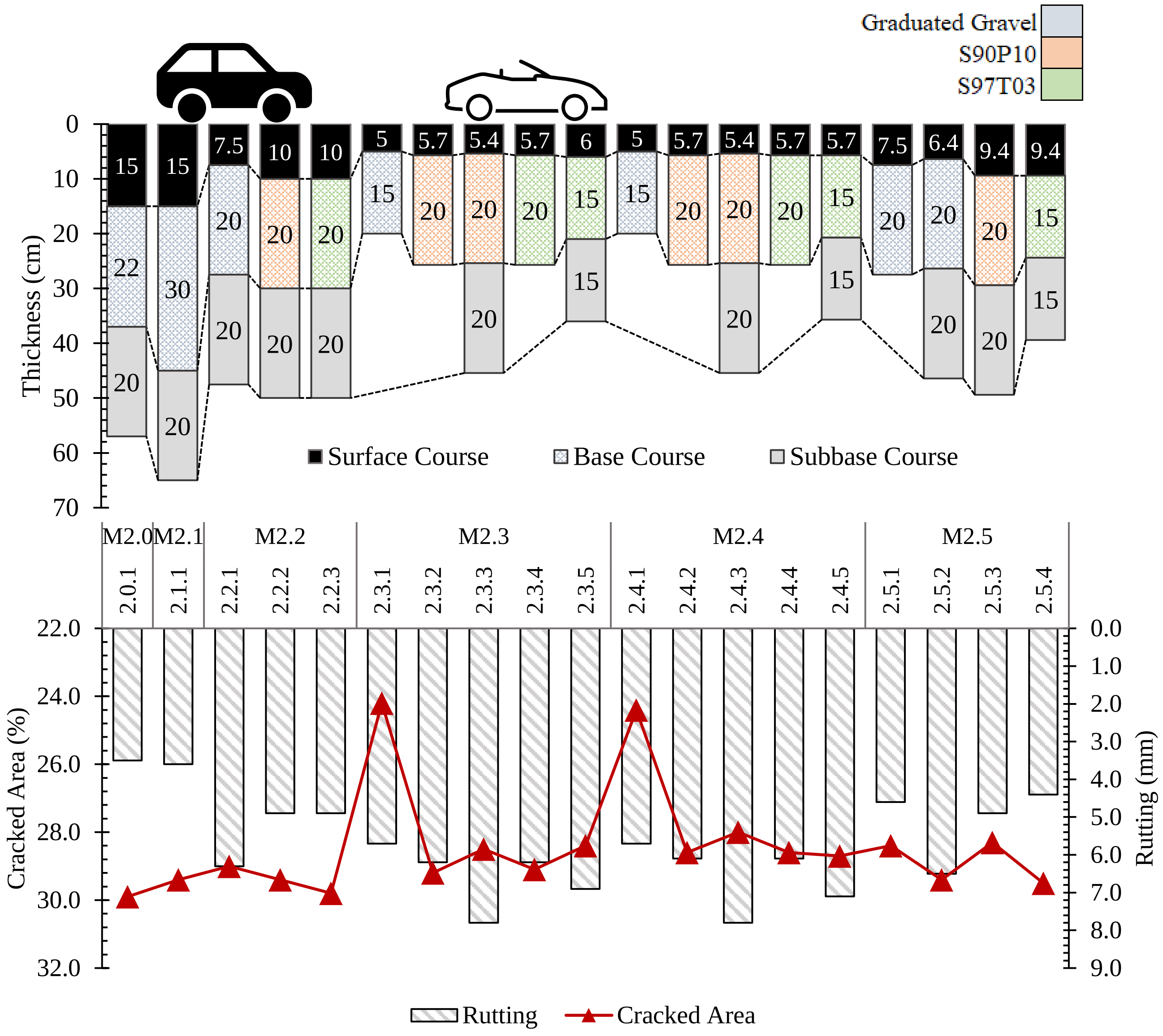


Figure 13: Functional unit characterization Part 2, with thickness for each pavement variant and functional parameters such as cracked area (%) and track sinking prediction (mm) by the end of the analysis period.

For the pavement structures with the HMA mixtures reported by Arao et al, (2017), the same tendency of surface course thickness reduction was reached from the software, decreasing from 15 cm to 7.5 cm with the use of M2.2 and M2.5 mixtures and 5 cm with M2.3 and M2.4 mixtures. With the use of the alternative base course with natural Brazilian soil improved with RPET, surface course maintained an acceptable reduced thickness, particularly for the structures with the M2.3 and M2.4 mixtures. Rutting and cracked area results are considered acceptable and on range with the results of Ferreira et al, (2022).

3.2 Life Cycle Inventory

3.2.1 Primary Data

The primary data used in this study consist of: (1) the hot mix asphalt mass proportion for the conventional and sustainable pavement structures, and (2) the equipment efficiency and resource consumption taken from the Work-Costs Reference System (SICRO), a Brazilian federative system proposed by the National Department for Infrastructure and Transport (DNIT). The cost compositions are taken exclusively for Brasília, Federal District of Brazil, and are summarized in Table 9.

Table 9: Cost Composition from SICRO, applicable to the Federal District for January 2022

ID	Name
4011462	Hot Mixed Asphalt Pavement - Class C - Extracted Sand and Produced Sand (T)
6416077	Hot Mixed Asphalt plant production - Class C - Extracted Sand and Produced Gravel (T)
4816020	Dredge extracted sand with pump (m^3)
4816012	Produced gravel in 80 m^3/h production plant (m^3)
4816010	Crushed rock with drill on track (m^3)
4011275	Base or Subbase course with graduated produced gravel (m^3)
6416039	Graduated Gravel Production with gravel produced in plant of 300 t/h (m^3)
4011209	Subgrade grading (m^2)

For each cost composition, the list of equipment used with its hour usage is selected for the overall fuel consumption volume, as being the result of the quantity of respective equipment for activity multiplied by the power of the equipment, hours of use, and by the fuel combustion ratio value.

3.2.2 Secondary Data

The main life-cycle inventory database for secondary data comes from Federal Highway Administration/MTU Asphalt Pavement Framework, integrated with the United States Environmental Protection Agency (US EPA) library in the Federal LCA Commons repository (LCA Commons, 2022). This database compiles the upstream flows and resources for most of the processes involved in the supply chain for pavement structures with a spatial scope of North America. These upstream processes are divided into the following categories:

1. Domestic electricity supply. The energy supply chain was adapted for the Brazilian Energy Balance, considering the domestic electricity supply by source in 2020, as presented in Figure 14 (EPE, 2020). The upstream data are adapted from the inventory database.

2. Raw materials (mining, extraction, and processing). Upstream data for raw materials processing and supply.
3. Transportation. Upstream data for resource consumption and emissions related to transportation activities.
4. Fuel combustion (diesel, gasoline, fuel oil, lignite coal, LPG). Upstream data for resource consumption and emissions related to fuel combustion.
5. Principal processes. Upstream data for resource consumption and emissions related to the asphalt binder, HMA production, and RPET reclamation. The life cycle inventory data with values and references is annexed in the Supplementary Materials.

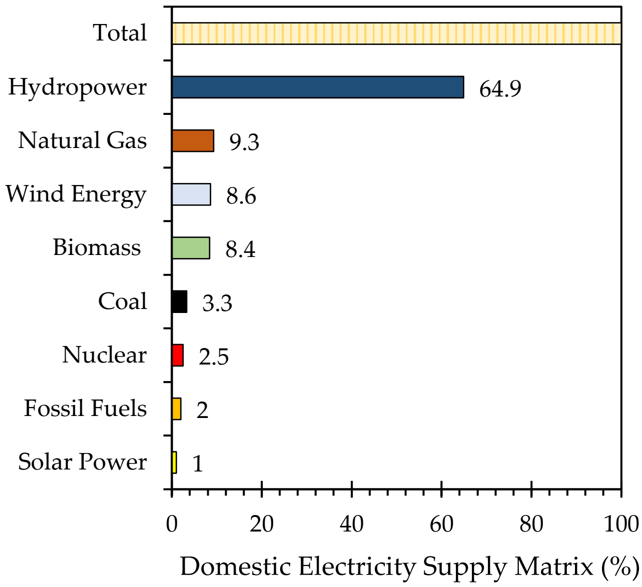


Figure 14: Brazilian domestic energy supply by source in 2020.

3.3 Life Cycle Impact Assessment and Interpretation

3.3.1 Impact Assessment Methodology

The methodology for environmental impact assessment applied is the tool for the reduction and assessment of chemical and other environmental impacts "TRACI 2.0" developed by the US EPA in 2003 and revised in 2011 (Bare, 2011). It allows for the quantification of stressors that have potential effects for sustainability metrics and impact assessment, such as ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, human health criteria-related effects, human health cancer, human health noncancer and ecotoxicity. Table 9 shows those units for each indicator characterized and the environmental component in which its effect is measured.

Table 10: TRACI 2.0 Environmental Impact indicators

ID	Indicator	Unit	Media
I-1	Acidification	kg SO2 eq	Air
I-2	Eutrophication	kg N eq	Air, water
I-3	Freshwater ecotoxicity	CTU eco	Urban/non-urban air, fresh water, seawater, natural soil, agricultural soil
I-4	Global warming	kg CO2 eq	Air
I-5	Human health—cancer	CTU cancer	Urban/non-urban air, fresh water, seawater, natural soil, agricultural soil
I-6	Human health—noncancer	CTU noncancer	Urban/non-urban air, fresh water, seawater, natural soil, agricultural soil
I-7	Human health—particulate matter	PM 2.5 eq	Air
I-8	Ozone depletion	kg CFCx10-11 eq	Air
I-9	Smog formation	kg O3 eq	Air

Within an LCA, the TRACI utilizes the amount of the chemical emission or resource used and the estimated potency of the stressor. Such potency depends on each chemical for the corresponding impact, which is a characterization factor. The overall Equation (1) applied is listed:

$$I^i = \sum_{xm} CF^i_{xm} * M_{xm}, \tag{1}$$

where I^i = the potential impact of all chemicals (x) for a specific impact category of concern (i); CF^I_{xm} = the characterization factor of chemical (x) emitted to media (m) for impact category (i), M_{xm} = the mass of chemical (x) emitted to media (m).

The management of all the life-cycle inventory, upstream processes, and impact assessment methodology is performed through the software OpenLCA® an open-source and versatile software developed for use in Life Cycle Assessment (GreenDelta, 2022).

3.3.2 Normalization and Weighting for Environmental Score

The normalization and weighting are optional stages of an LCA that can be applied to process the results into a more understandable perspective for the user. The normalization step consists of the magnitude of the division of each impact indicator in relation to a reference, which can be external or internal from the same product system, such as the maximum result of all cases evaluated. The weighting stage consists of a secondary ponderation of each normalized indicator, multiplied by a category weight defined by a stakeholder perspective. For this study, an internal normalization procedure is applied for each indicator, and a set of weights defined for the TRACI 2.0 methodology is implemented and detailed in Table 10. (Gloria et al., 2007)

Table 11: Weights for each impact category indicator for an average user, under a medium-term time horizon.

Environmental Score Values	
Indicator	Medium-term time horizon
Acidification	2
Eutrophication	5
Freshwater ecotoxicity	11
Global warming	43
Human health—cancer	6
Human health—noncancer	2
Human health—particulate matter	3
Ozone depletion	2
Smog formation	4

The interpretation of the environmental score (ES) follows an inverse logic of product scoring, in which the lowest ES will indicate the better environmental performance due to smaller characterized environmental impact pondered values. In the other hand, a high ES will indicate the worst environmental performance due to higher pondered values.

4 RESULTS

The current chapter presents the results of the LCIA step for the declared and functional units, in terms of characterized environmental impacts bulk results, normalized and environmental score comparison. Subsequently, a sensibility analysis is presented for RPET quantity in contrast of global warming potential and environmental score for each case.

4.1 Declared Units Comparison and Interpretation

4.1.1 DU – LCIA Results: bulk and normalized comparison

The declared unit environmental life-cycle impact assessment results are presented in Figure 15. The declared units of M1.2 and M2.5 presented the higher results in all category impacts, with light variation on relative comparison. These represents the HMA mixtures with higher RPET quantity from each author.

The impact of eutrophication resulted with more differential results in function of the declared units, with the Conventional HMA ones being with the lowest value.

The impact of global warming potential maintained the same tendency, with 129.16 Kg CO_2 eq as the lowest result for the M1.0, which represents the conventional HMA mix from Ferreira et al, (2022), and 169.30 Kg CO_2 eq for the higher result for the M1.2 with 8% of RPET micronized per filler volume substitution.

The DU of Arao et al (2017) resulted with less variation, but followed the same tendency, with the mixtures with higher RPET percentage presenting higher characterized impact values.

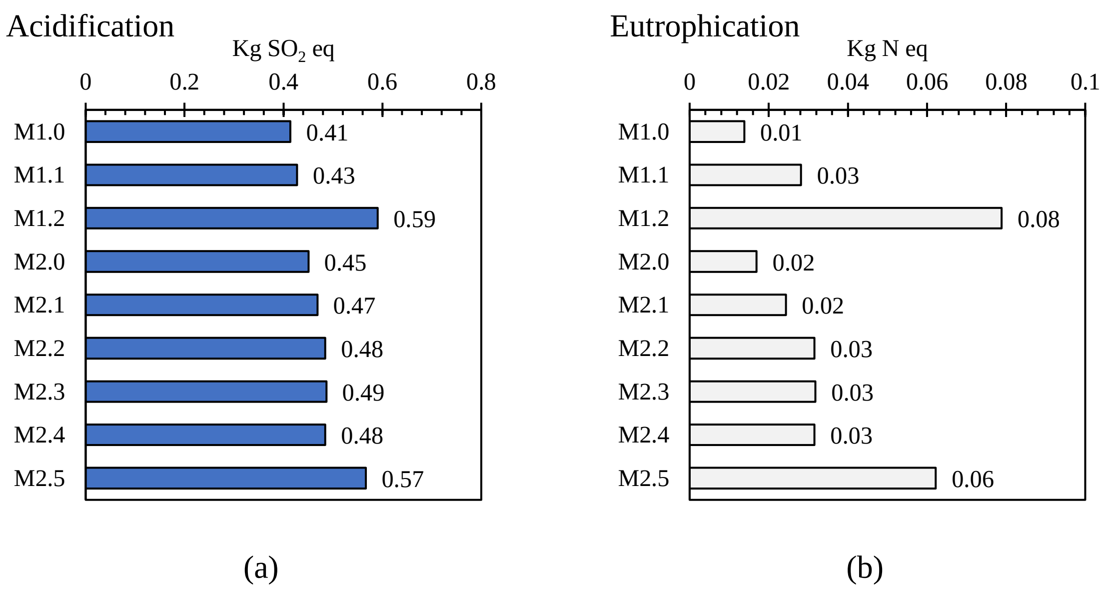


Figure 15. Cont.

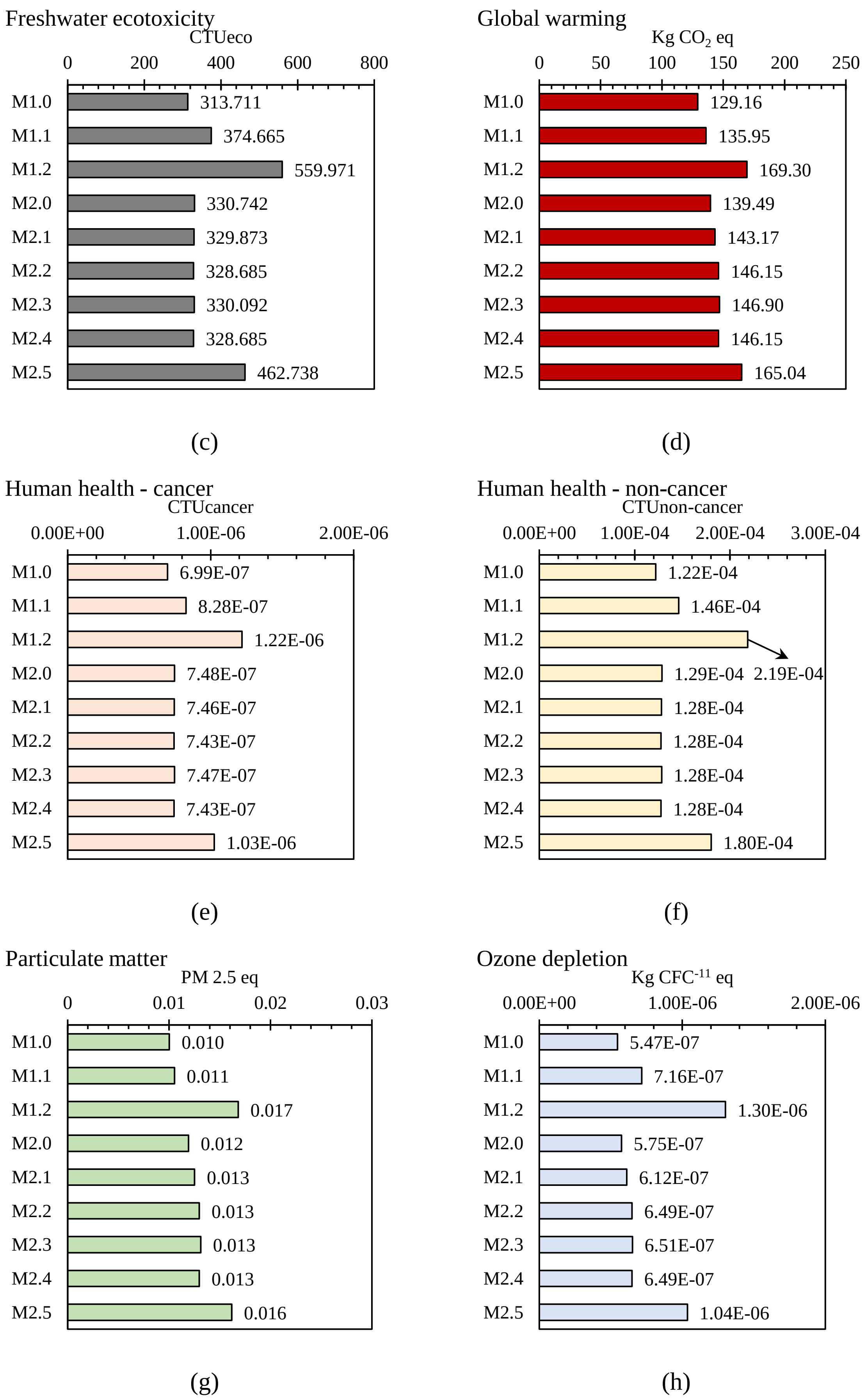
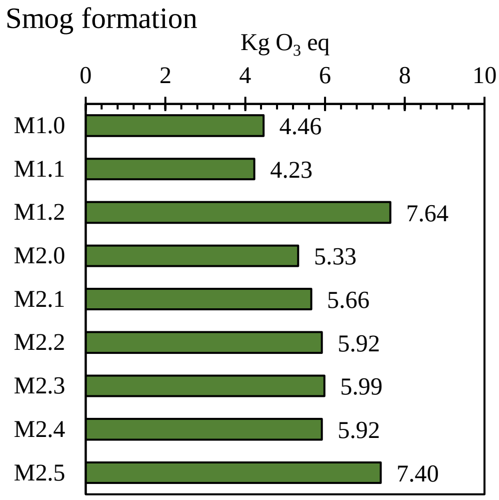
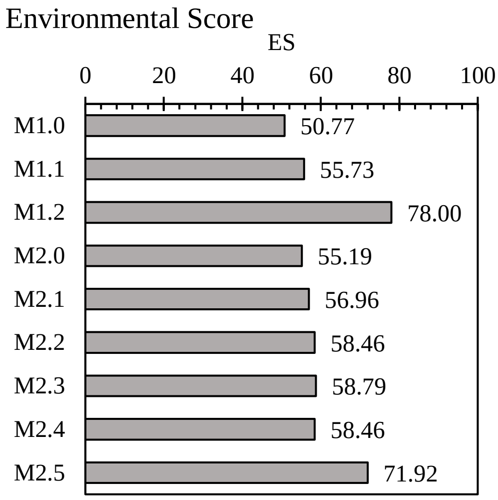


Figure 15. Cont.



(i)



(j)

Figure 15: Declared Unit's LCIA characterized results: (a) acidification; (b) eutrophication; (c) freshwater toxicity; (d) global warming; (e) human health—cancer; (f) human health—noncancer; (g) human health—particulate matter; (h) ozone depletion; (i) smog formation and (j) Environmental Score.

The relative comparison is performed by dividing each impact value by the higher result in the dataset. In Figure 16 and Figure 17 are presented the internal normalization comparison for the DU corresponding to Ferreira et al, (2022) and Arao et al, (2017), respectively.

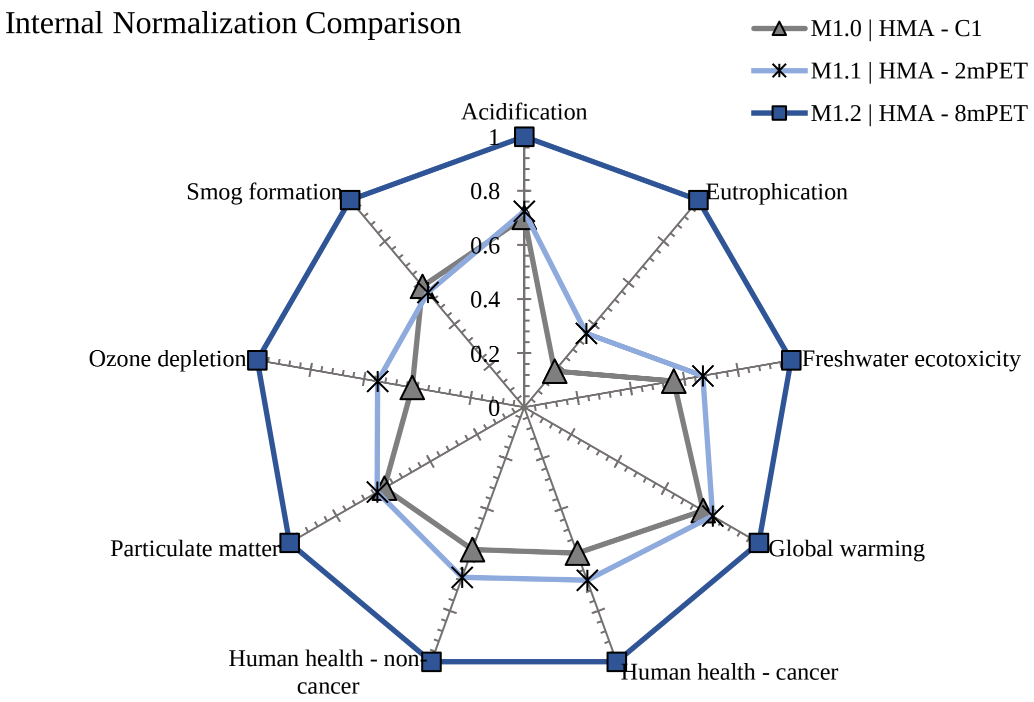


Figure 16: Internal Normalization comparison for environmental impacts of declared units - Part 1: Comparison for Ferreira et al (2022) HMA mixes.

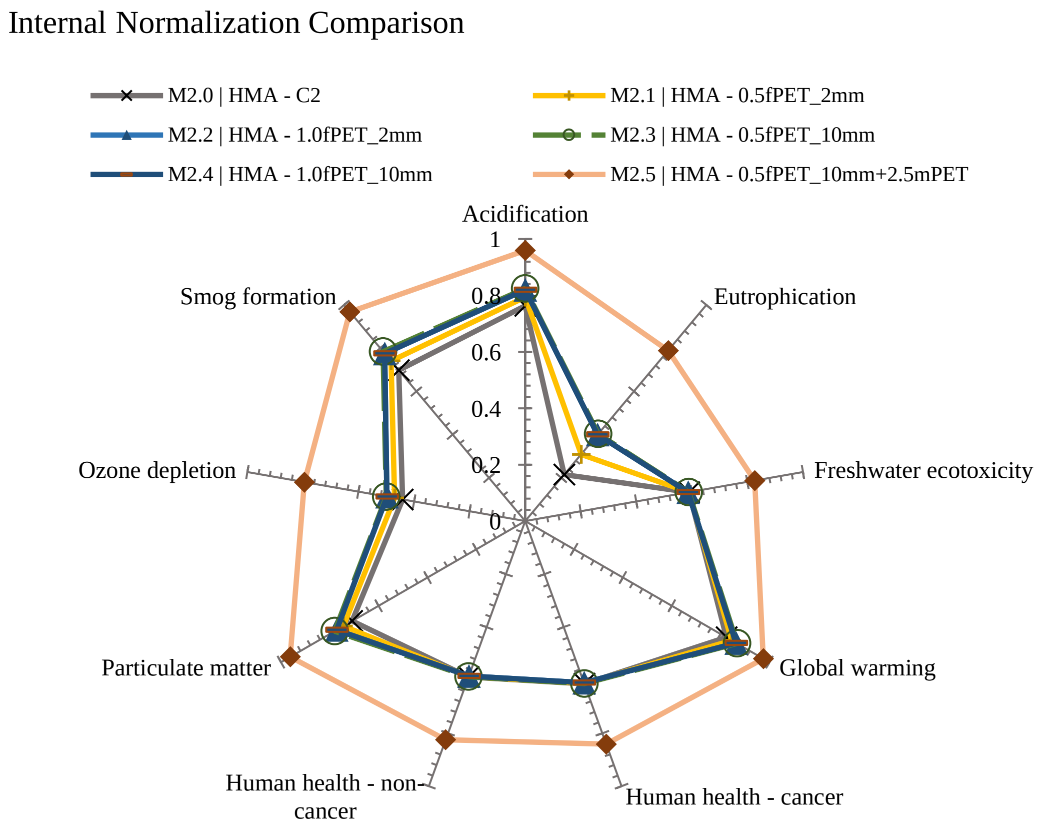


Figure 17: Internal Normalization comparison for environmental impacts of declared units - Part 2: Comparison for Arao et al, (2017) HMA mixes.

The M1.2 is the declared unit with higher relative results, so for each characterized impact it relative value is 1. Following it closely is the M2.5, which also resulted with relative values close to 1, but less than M1.2.

The other DU presented a similar overall behavior in the radar chart, with similar results and a high contrast in just the impact of eutrophication. It denotes a sensibility of such impact to the addition of RPET into the mixtures. Little variations in characterized impact values can be attributed to gravel and filler quantities variations, and small percentage variation of optimal asphalt content.

4.1.2 DU's Environmental Score

Following the weighting criteria for the normalized results, the declared unit's ES is presented in Figure 18 and Figure 19 for Ferreira et al (2022) and Arao et al (2017) mixtures respectively. It illustrates the impacts contribution by DU, as well as the overall total pondered ES value.

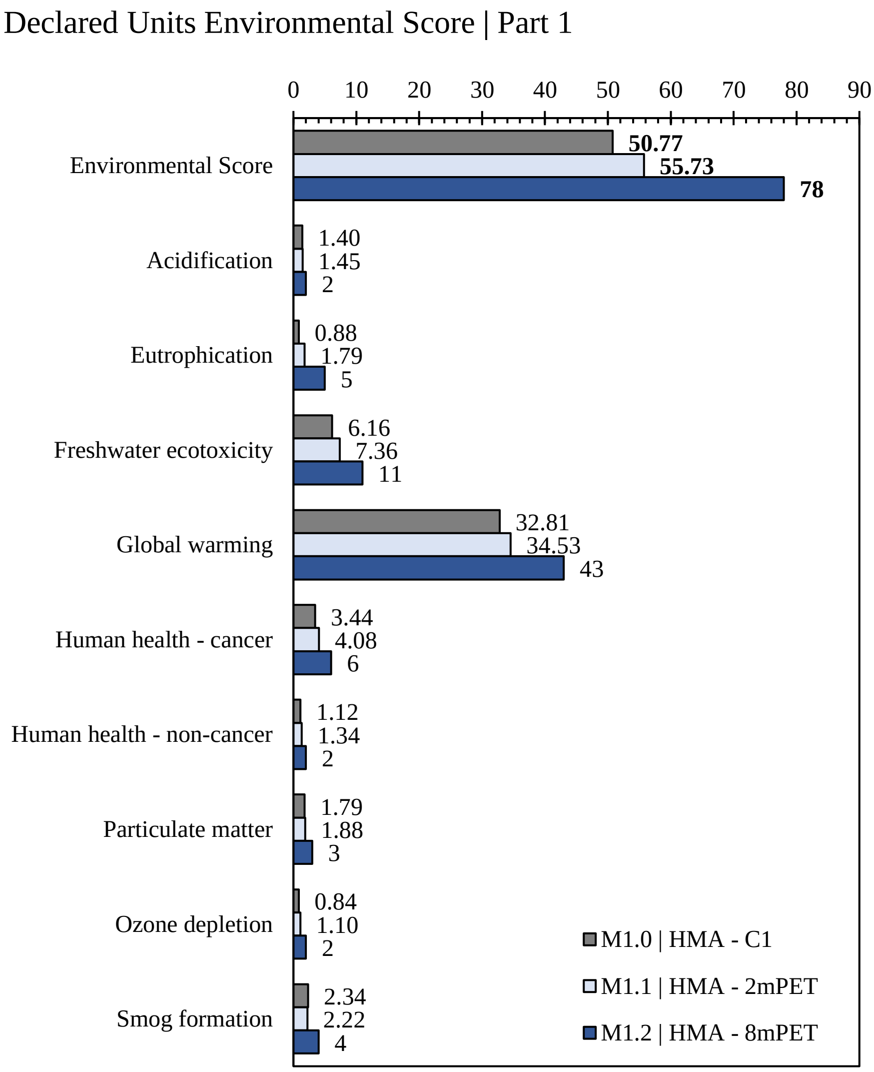


Figure 18: Declared Unit's Environmental Score – Part 1.

Following the ES criteria previously stablished, for the DU from Ferreira et al, (2022), the mixture with better environmental performance was the M1.0, which correspond to the conventional HMA mix, with an ES = 50.77. The mixture with worst environmental performance was the M1.2, with an ES = 78, representing a maximum increase of + 53.6 % in pondered impacts, in decremental of the environmental performance by the addition of RPET to the mixtures.

For the DU from Arao et al, (2017), the mixture with better environmental performance was the M2.0, which also correspond to the conventional HMA mix, with an ES = 55.19. The mixture with the worst environmental performance was the M2.5, with an ES = 71.92, representing a maximum increase of + 30.31% in pondered impacts, in decremental of the environmental performance by the addition of RPET to the mixtures.

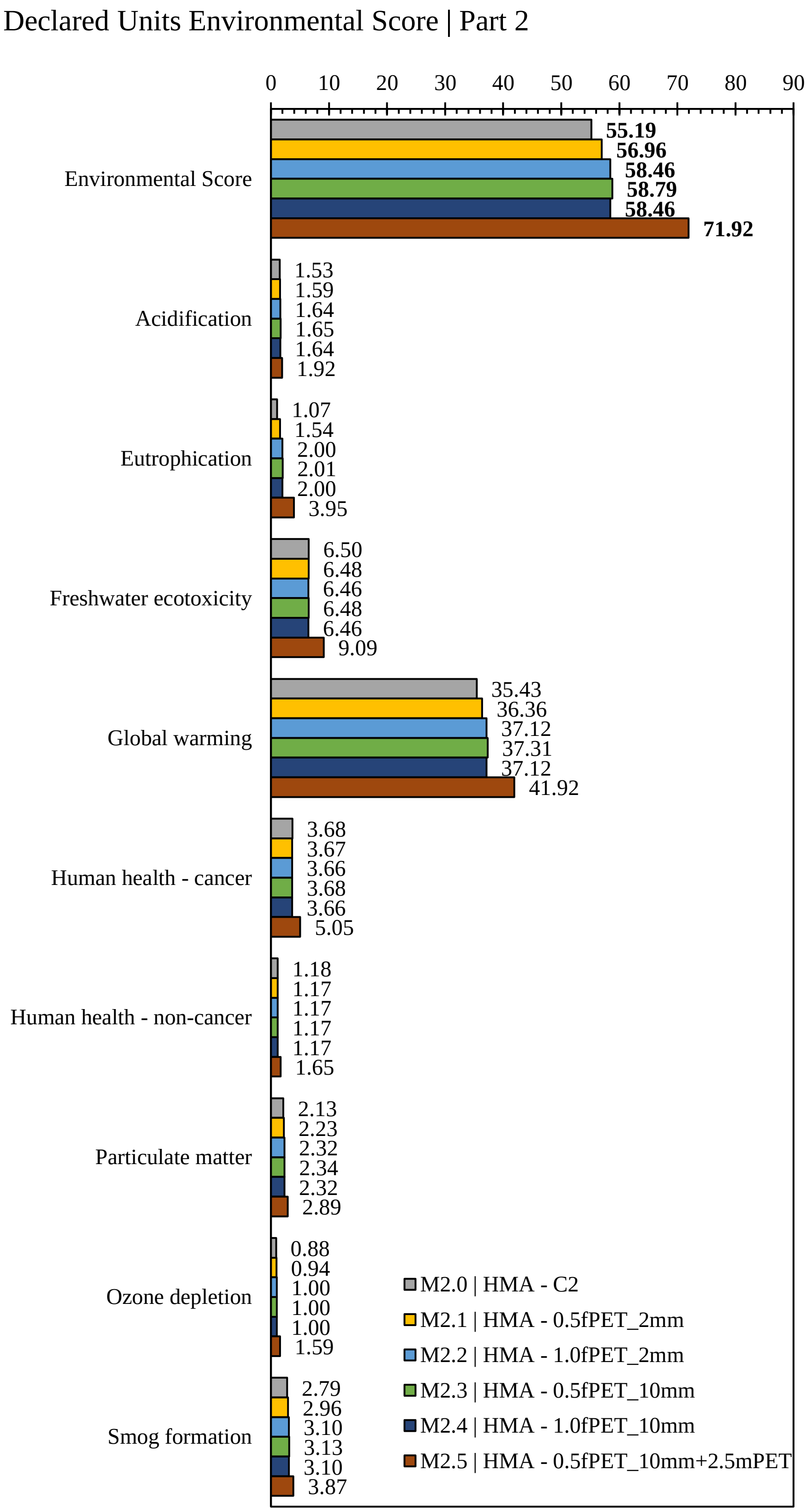


Figure 19: Declared Unit's Environmental Score – Part 2.

4.1.3 Sensitivity Analysis

A sensibility analysis was developed to explore the tendency of the impact in global warming potential (GWP) and environmental score by the increase of RPET added in each DU. In Figure 20, the net RPET mass is presented in contrast of the GWP impact. By creating a tendency graph between each impact value from each DU, for each dataset can be appreciated a linear increase of GWP, proportional to the amount of Net RPET present in each DU. By means of combining both dataset from each author, it can be deduced that a HMA mixture from Ferreira et al (2022) with approximately 12 Kg/ton of RPET will have the GWP impact, measured in Kg CO_2 eq, as a conventional HMA mix from Arao et al (2017) dataset, in terms of plant production.

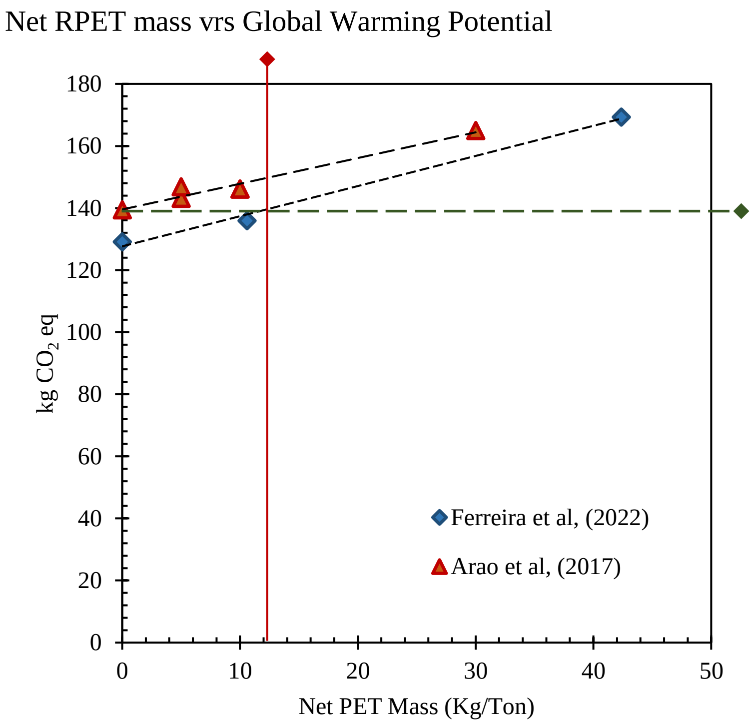


Figure 20: Sensibility Analysis Chart for net PET mass addition for each DU versus Global Warming Potential Impact.

In Figure 21 the net RPET mass is presented in contrast of the ES value for each DU. By creating a tendency graph between each ES value from each DU, for each dataset can be appreciated a linear increase of ES, proportional to the amount of Net RPET present in each DU. By means of combining both dataset from each author, it can be also identified that a HMA mixture from Ferreira et al (2022) with approximately 7 Kg/ton of RPET will have the environmental performance as a conventional HMA mix from Arao et al (2017) dataset, in terms of plant production.

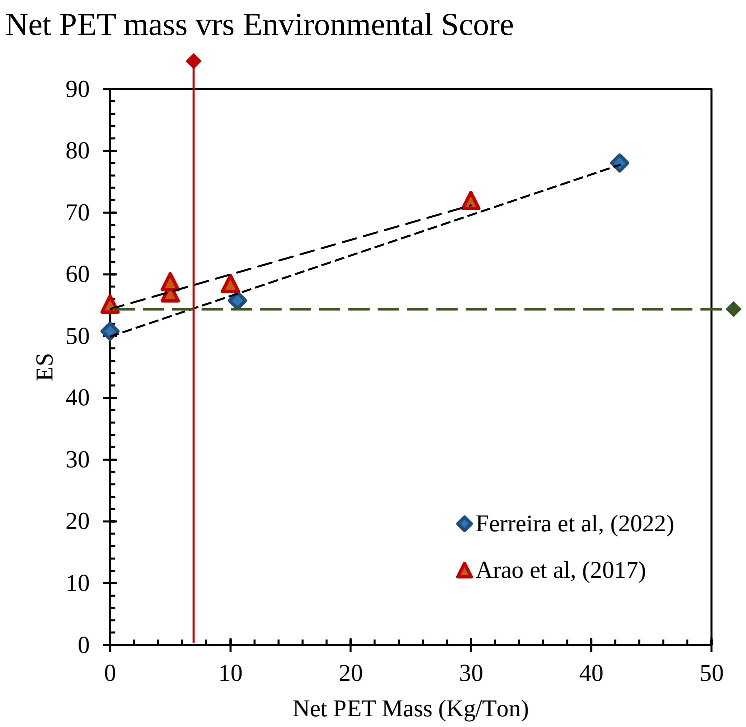


Figure 21: Sensibility Analysis Chart for net PET mass addition for each DU versus Environmental Score

4.2 Functional Unit Comparison and Interpretation

4.2.1 FU – LCIA Results: bulk and normalized comparison

The functional unit environmental life-cycle impact assessment results are reported as follow. In Figure 22 are reported the acidification and eutrophication impact values. In Figure 23, freshwater ecotoxicity and global warming impact values. In Figure 24, impacts on human health cancer and non-cancer. In Figure 25, impacts on particulate matter in human health and ozone depletion, and in Figure 26, impact in smog formation and the overall environmental score for each FU.

It shows the bulk results for characterized environmental impact values by each FU, presenting the same tendency for all impacts. In general, the FUs that represent pavement structures with reduced thickness presented smaller environmental impact values, up to the point in which the amount of added RPET negatively affects the environmental performance.

The FUs with the S90P10 base course presented the higher overall environmental impact values, as FU1.1.3, FU1.2.3, FU2.2.2 and FU2.5.3 with the highest values on environmental impacts.

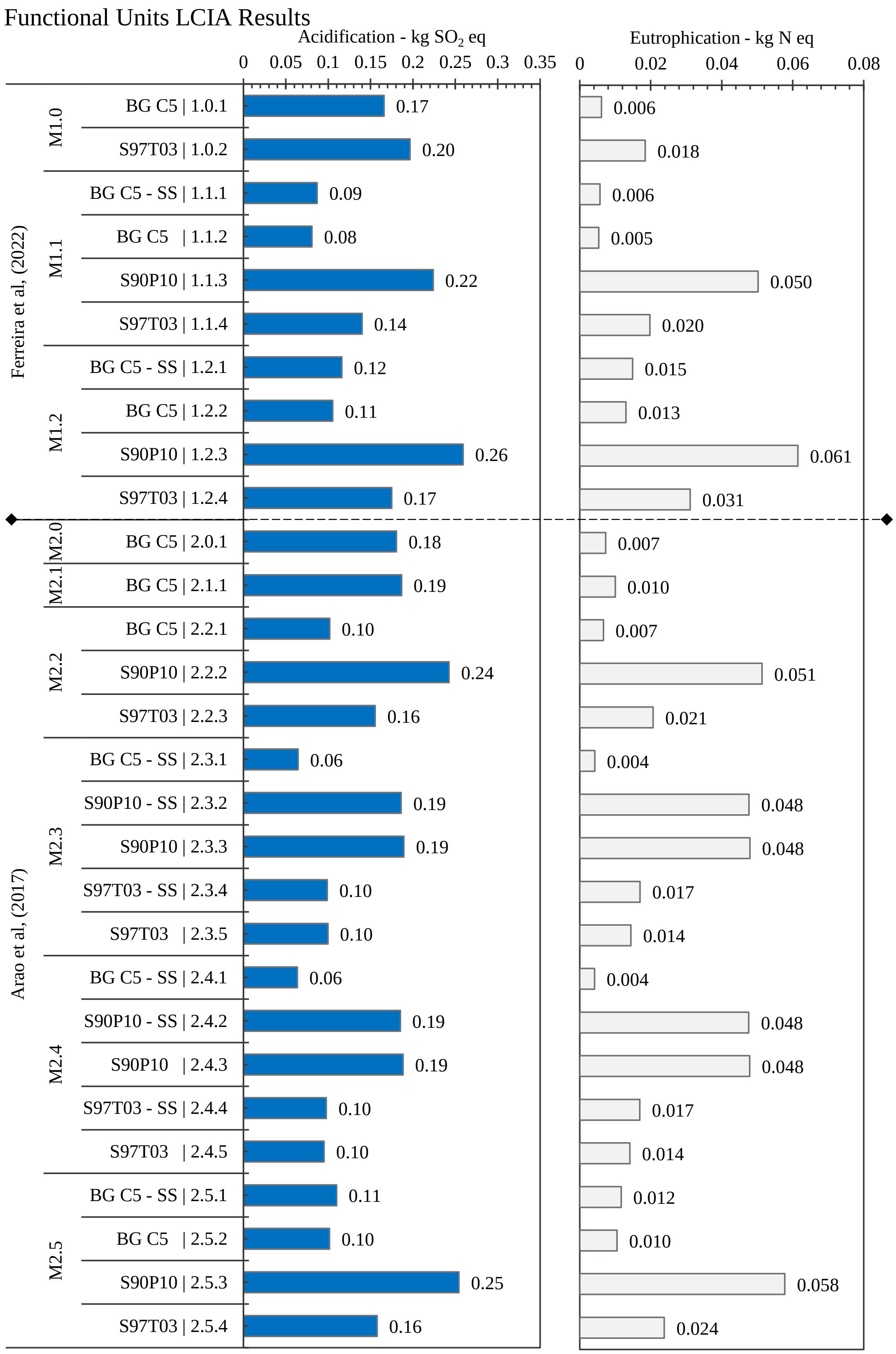


Figure 22: Functional unit's LCIA characterized results: acidification and eutrophication.

Functional Units LCIA Results

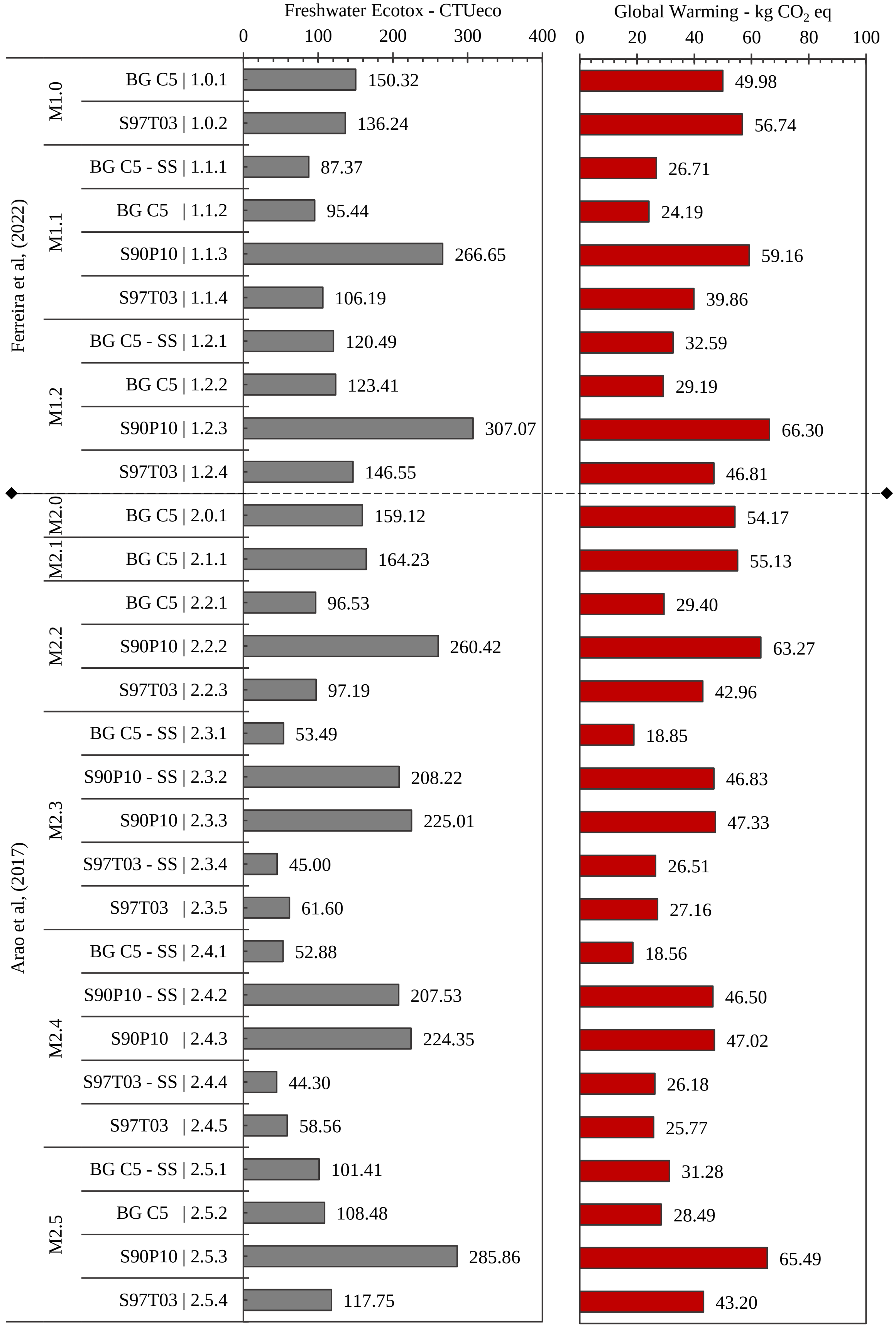


Figure 23: Functional unit's LCIA characterized results: freshwater ecotoxicity and global warming.

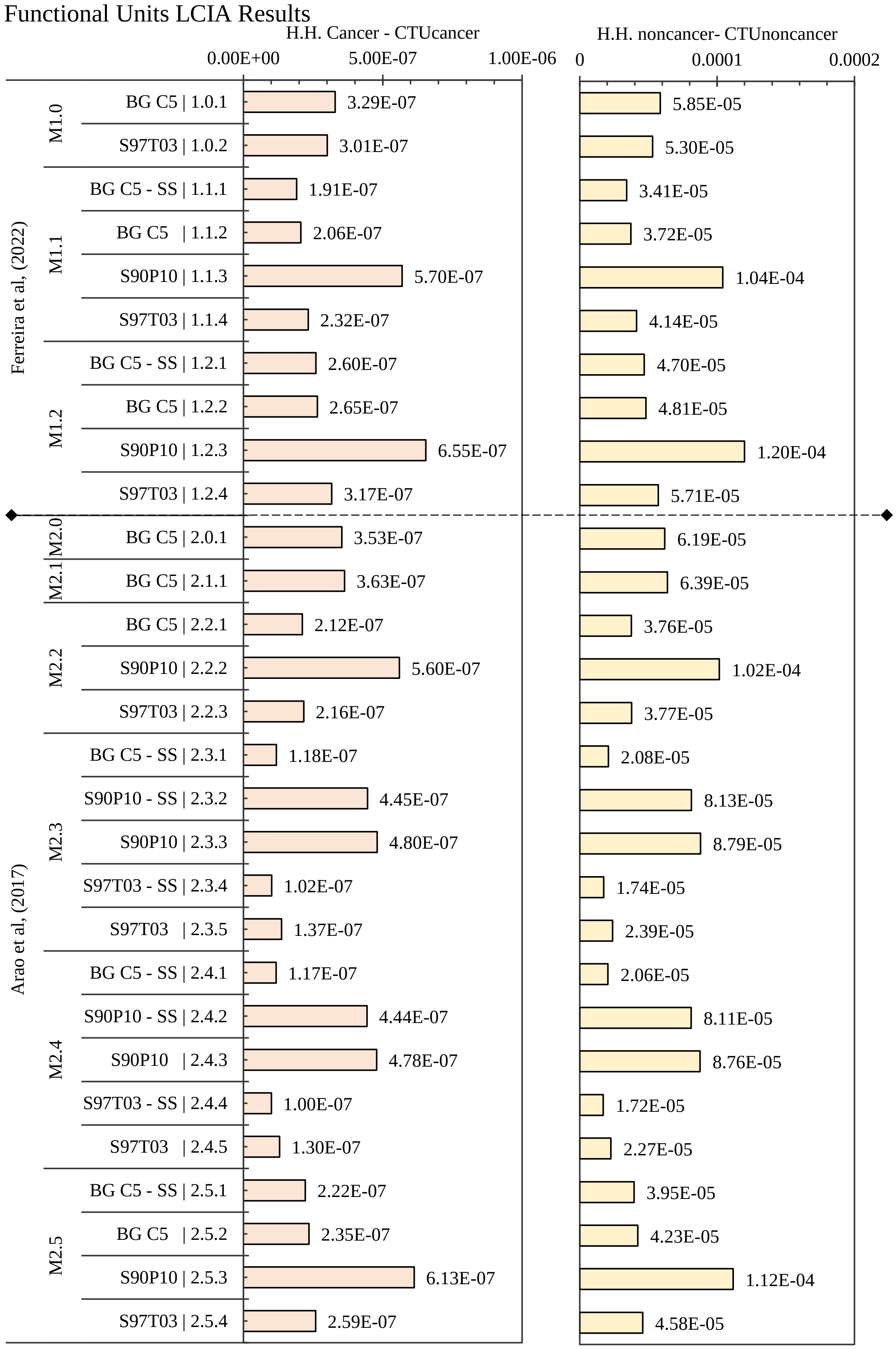


Figure 24: Functional unit's LCIA characterized results: H.H. cancer and H.H. non-cancer.

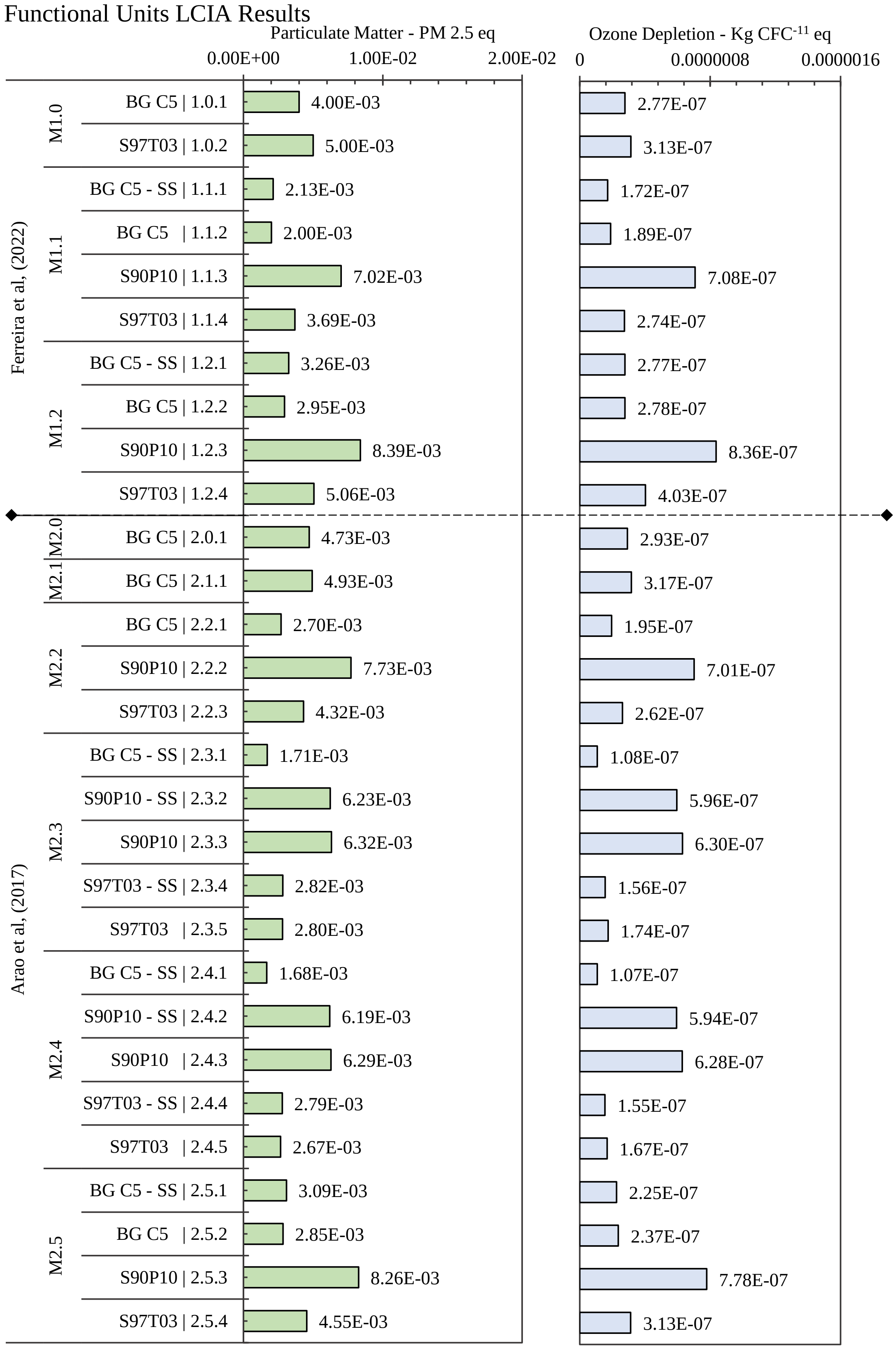


Figure 25: Functional unit's LCIA characterized results: Particulate Matter and Ozone Depletion.

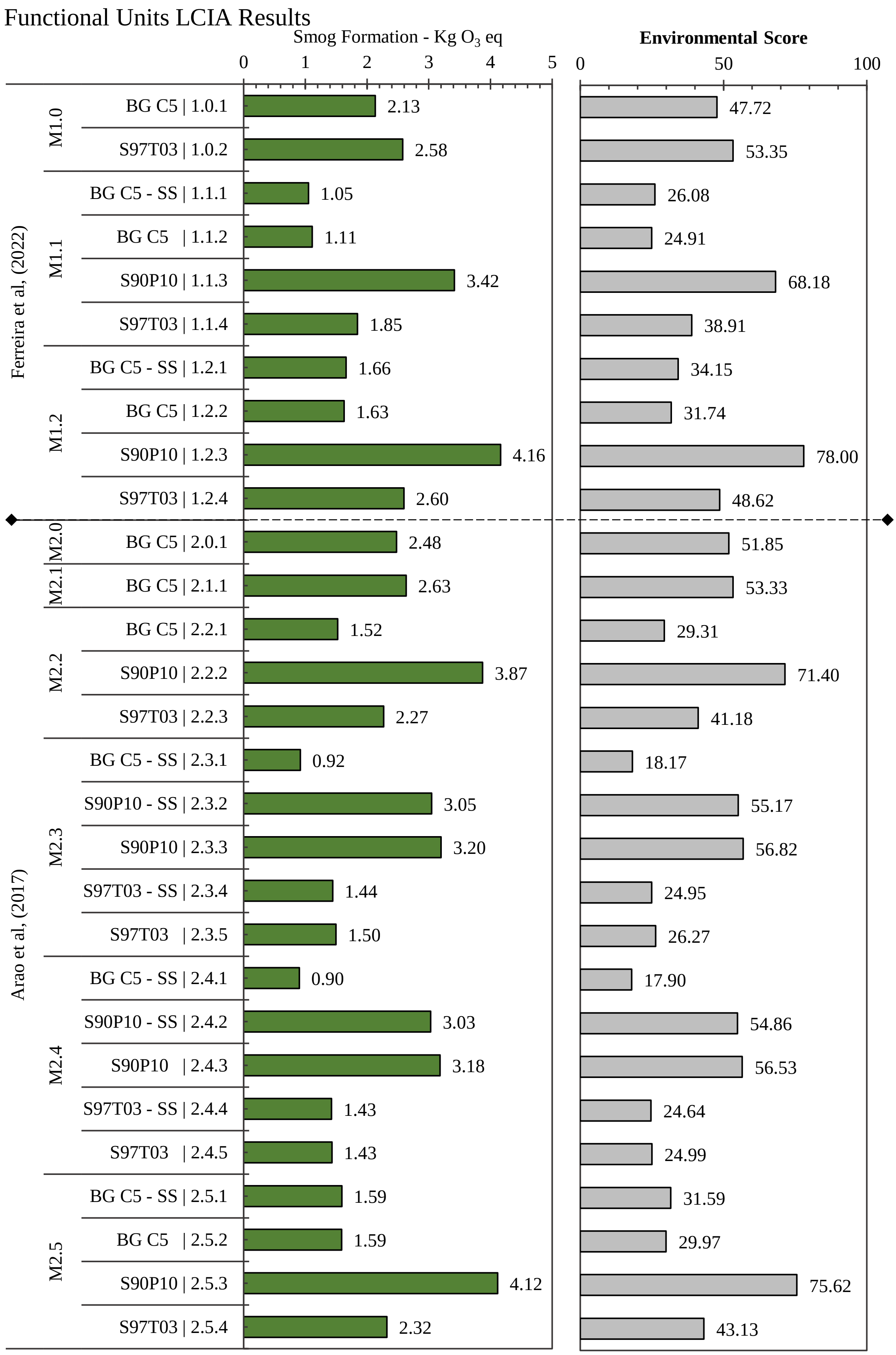


Figure 26: Functional unit's LCIA characterized results: Smog Formation and Environmental Score.

For the internal normalization comparison, radar charts were developed, and functional units were distributed by author and by declared unit main mixture. In Figure 27 are presented the FUs from Ferreira et al (2022) HMA mixtures.

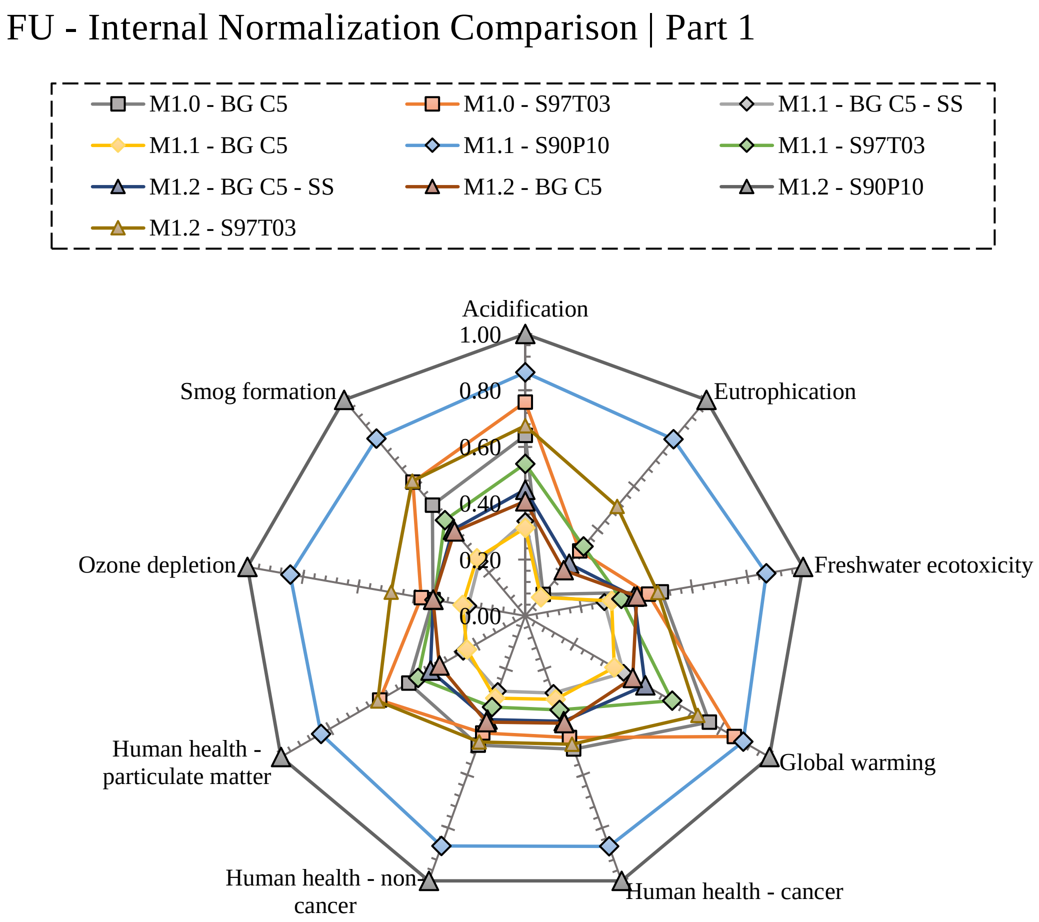


Figure 27: Internal normalization comparison for environmental impacts of functional units - Part 1.

In Figure 27 is identified the FU with the maximum relative result. FU 1.2.3, which uses the M1.2 mixture and the S90P10 base course. The second highest result is presented by FU 1.1.3, which uses the M1.1 mixture and the S90P10 base course too. The rest of the FUs follow the same graph pattern, with the global warming impact and acidification impact the ones with more values dispersion. The eutrophication impact presents the higher relative differential among all characterized impacts. The FUs with lower relative result are the FU 1.1.1 M1.1 mixture with BG C5 without subbase and FU 1.1.2 M1.1 mixture with BG C5.

In Figure 28 are presented the FUs from Arao et al, (2017) M2.0, M2.1, M2.2 and M2.3 mixtures. The FU with higher relative impact values is the FU 2.2.2, with the M2.2 mixture and the S90P10 base course, with values close to 1. Closely behind are the two FU from the M2.3

mixture and S90P10 base course, FU 2.3.2, and FU 2.3.3. They also share a similar graph pattern, with similar relative values on all characterized impacts.

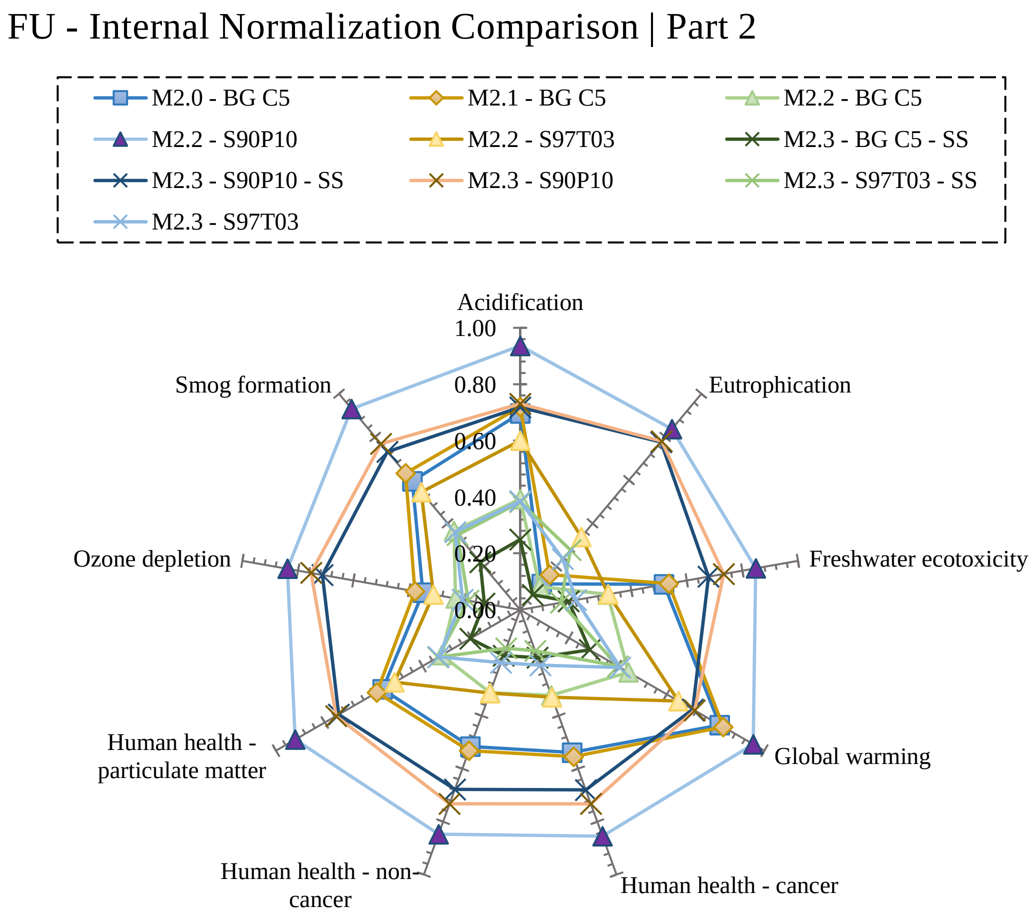


Figure 28: Internal normalization comparison for environmental impacts of functional units - Part 2.

The FU with lower relative impact values is the FU 2.3.1, with the M2.3 mixture, graduated gravel base course and without subbase. The rest of the FUs follow the same graph pattern, with the global warming impact and acidification impact the ones with more values dispersion. The eutrophication impact presents the higher relative differential among all characterized impacts.

In Figure 29 are presented the FUs left from Arao et al, (2017), M2.4 and M2.5. The FUs with the higher relative values are the FU 2.5.3, with the M2.5 mixture and S90P10 base course, follow behind by the FU 2.4.2 and FU 2.4.3, with the M2.4 mixtures and S90P10 base course.

The FU with lower relative impact values is the FU 2.4.1, with the M2.4 mixture and the graduated gravel base course, without subbase. The rest of the FUs follow the same graph pattern, with the global warming impact and acidification impact the ones with more values dispersion. The eutrophication impact presents the higher relative differential among all characterized impacts.

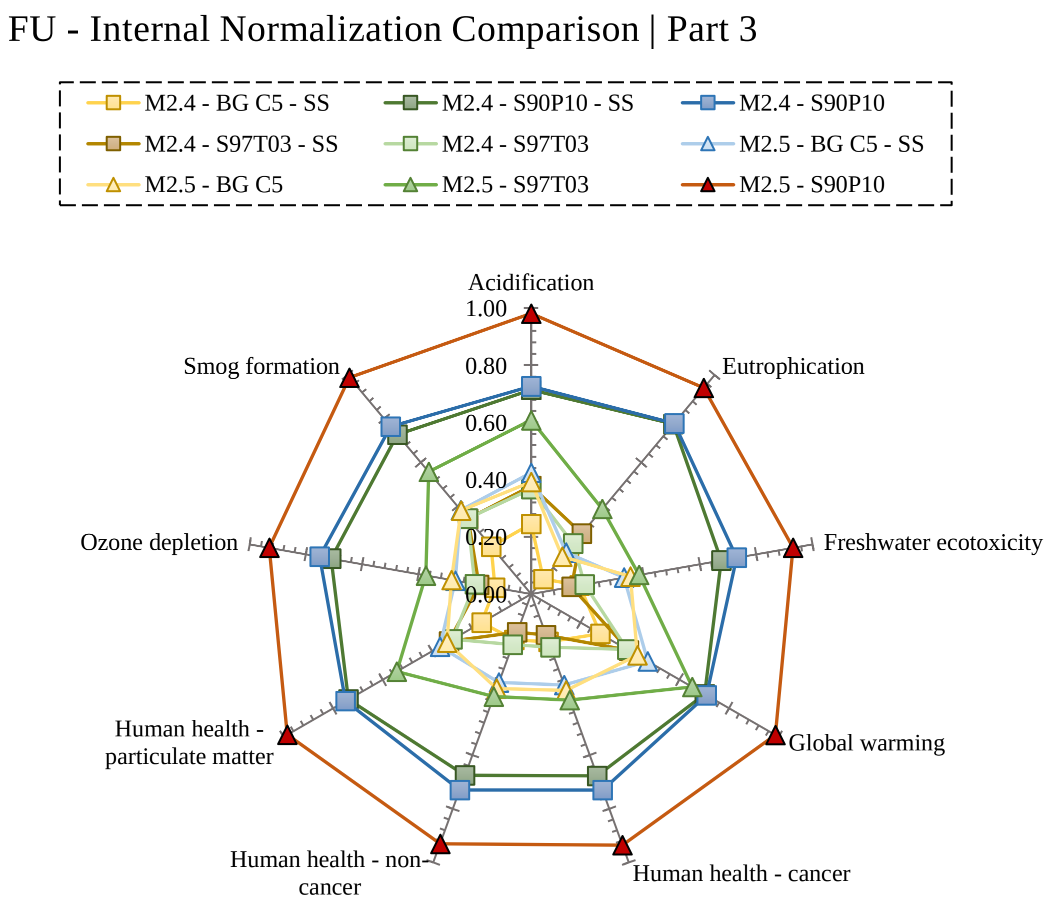


Figure 29: Internal normalization comparison for environmental impacts of functional units - Part 3

4.2.2 Process contribution in characterized environmental impacts for functional units.

A process-oriented results for characterized environmental impacts was performed to assess the sensibility of the contribution of the upstream processes, and to identify the main activities with environmental burden for the FU. The global warming potential and eutrophication impacts were selected for the analysis, as they are the main concern for stakeholder, in the case of GWP, and were specially affected by the RPET addition on the pavement structures, in the case of the eutrophication.

In Figure 30, Figure 31 and Figure 32 are summarized the global warming process contribution for the functional units.

For global warming potential, the process contribution order, from major to minor, for the functional units is identified as the HMA plant production in first place, followed by the asphalt upstream process for supply and refining. In third place comes in average the domestic electricity supply, followed by various fuel combustion and transportation concept. Lastly the contribution of raw material processing and supply. Altogether, for each FU, the order of process contribution may vary.

Asphalt and HMA plant production processes are observed to be sensible to surface course thickness, with direct proportionality. They account for the bigger impact contribution for the FUs, this due to high quality primary data and its primordial place in the product system.

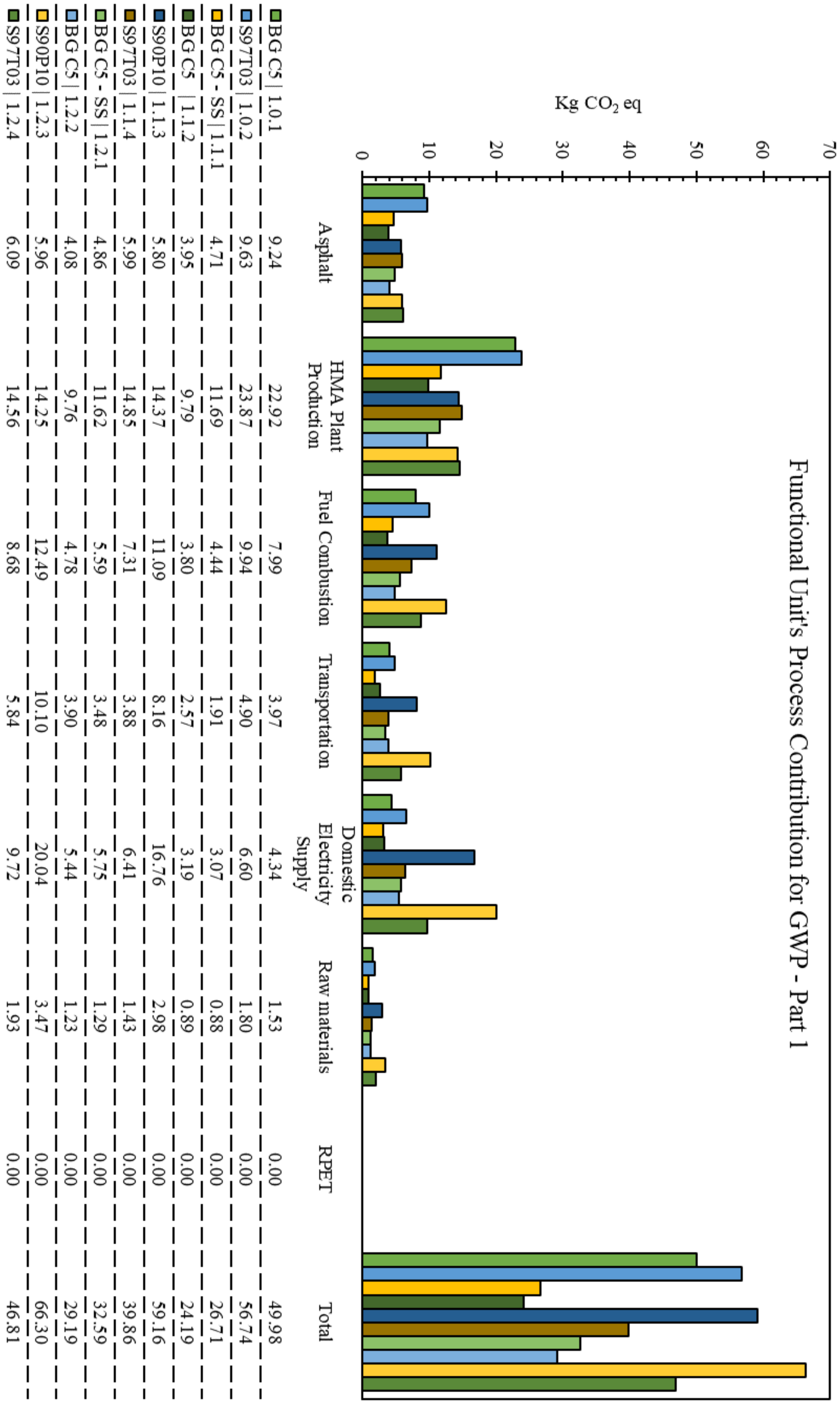
Fuel combustion, transportation and domestic electricity supply are observed to be sensible to RPET quantities in each FU, with high proportionality specially in the pavement structures with S90P10 base course.

Raw material extraction and supply are the lowest process contributor to the FUs due for its upstream location in the supply chain, sharing the environmental load with co-products and use of secondary data with a level of uncertainty.

RPET upstream processes are observed to not contribute to global warming potential, this due to the allocation rule of the environmental burden of the recycled material, with a net carbon balance equal to 0, and only contributing indirectly with domestic electricity consumption, fuel combustion and transportation.

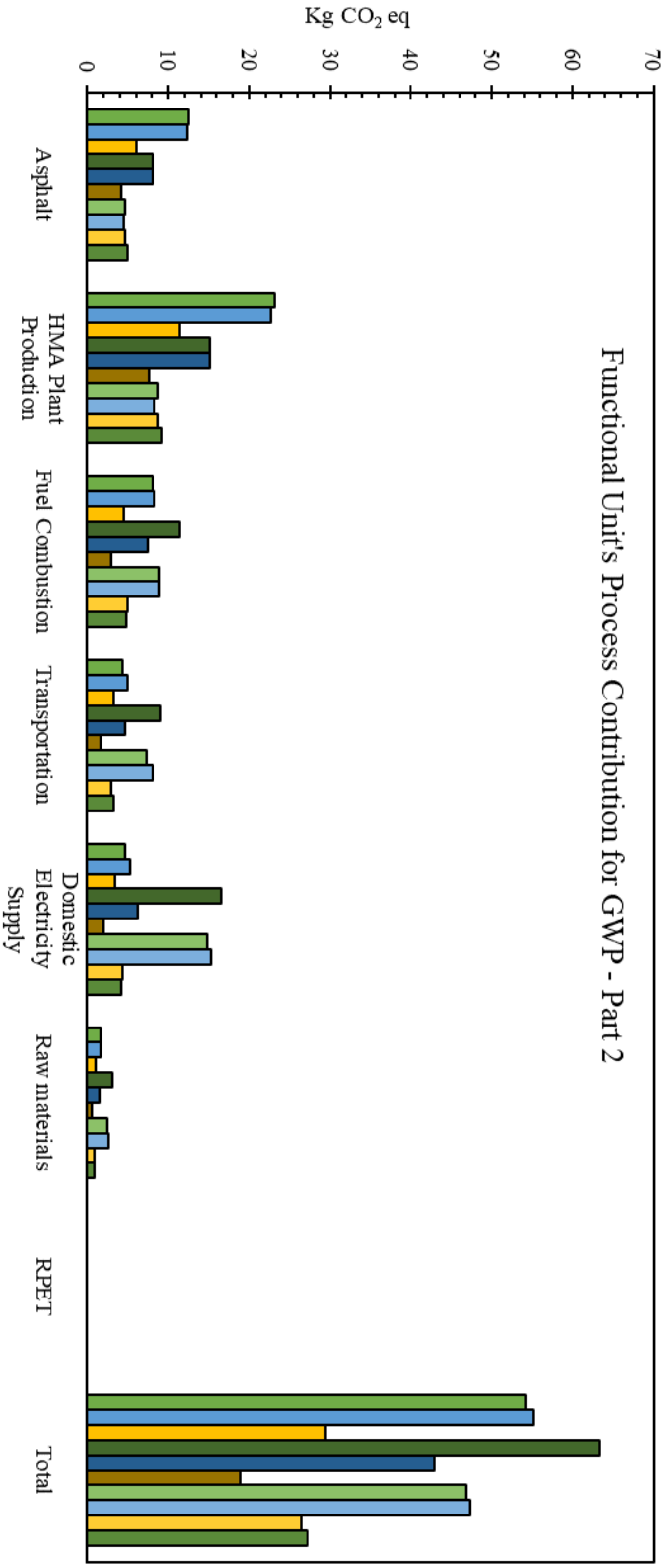
In Figure 33, Figure 34 and Figure 35 are summarized the eutrophication process contribution for the functional units.

In contrast of the global warming impact, with similar and hierarchical noticeable process contribution, the eutrophication impact is largely influenced by the addition of RPET in the pavement structures, with a small and almost negligible contribution by the rest of processes. The in-process activity contributing to eutrophication in the RPET recycling is the washing and cleaning of the bottles and flakes, removing the organic residues from the plastic. Such process is accounted as an increase of the chemical and biological oxygen demand in the effluent of the recycling facility, considered as an emission and characterized into the eutrophication impact category.



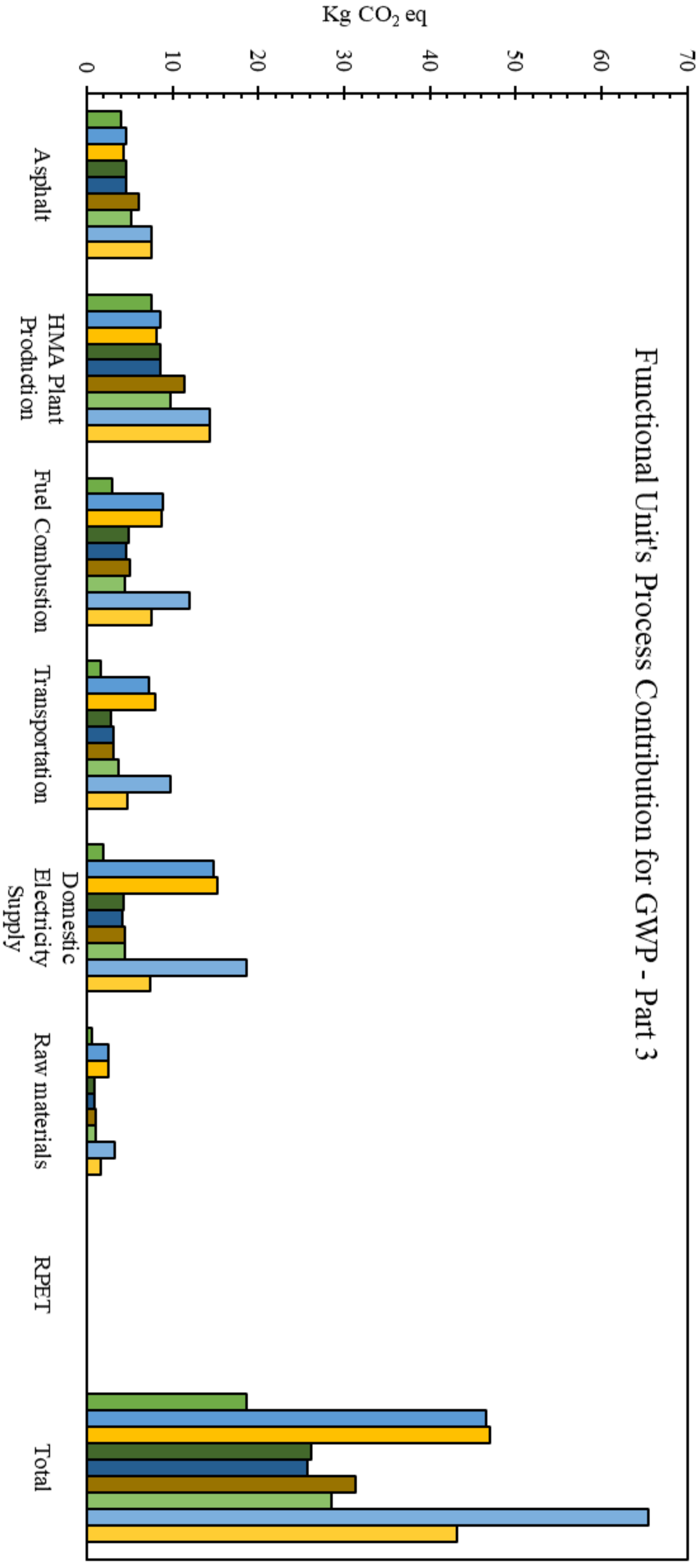
	Asphalt	HMA Plant Production	Fuel Combustion	Transportation	Domestic Electricity Supply	Raw materials	RPET	Total
BG C5 | 1.0.1	9.24	22.92	7.99	3.97	4.34	1.53	0.00	49.98
S97T03 | 1.0.2	9.63	23.87	9.94	4.90	6.60	1.80	0.00	56.74
BG C5 - SS | 1.1.1	4.71	11.69	4.44	1.91	3.07	0.88	0.00	26.71
BG C5 | 1.1.2	3.95	9.79	3.80	2.57	3.19	0.89	0.00	24.19
S90P10 | 1.1.3	5.80	14.37	11.09	8.16	16.76	2.98	0.00	59.16
S97T03 | 1.1.4	5.99	14.85	7.31	3.88	6.41	1.43	0.00	39.86
BG C5 - SS | 1.2.1	4.86	11.62	5.59	3.48	5.75	1.29	0.00	32.59
BG C5 | 1.2.2	4.08	9.76	4.78	3.90	5.44	1.23	0.00	29.19
S90P10 | 1.2.3	5.96	14.25	12.49	10.10	20.04	3.47	0.00	66.30
S97T03 | 1.2.4	6.09	14.56	8.68	5.84	9.72	1.93	0.00	46.81

Figure 30. Functional unit upstream process contribution for global warming potential impact – Part 1.



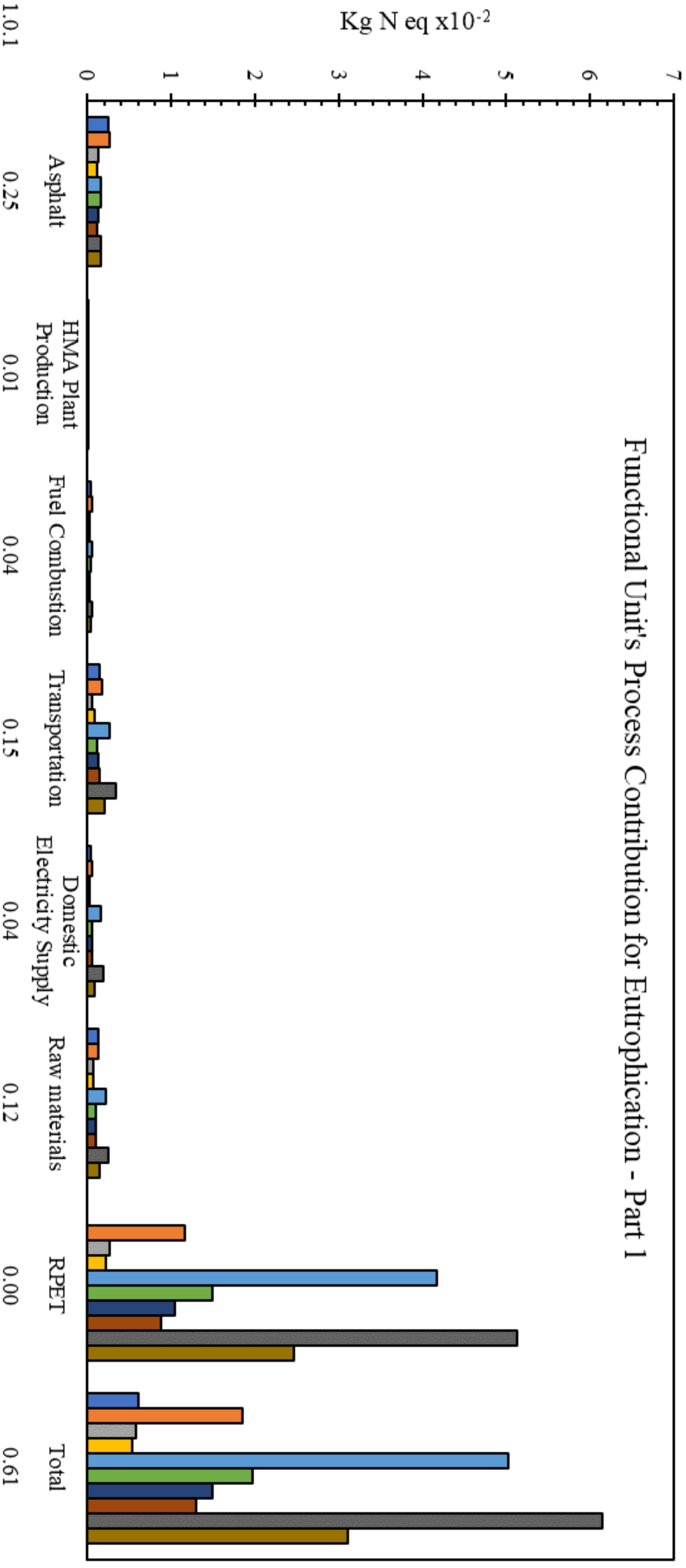
	Asphalt	HMA Plant Production	Fuel Combustion	Transportation	Domestic Electricity Supply	Raw materials	RPET	Total
BG C5 | 2.0.1	12.48	23.07	8.08	4.38	4.56	1.59	0.00	54.17
BG C5 | 2.1.1	12.25	22.64	8.31	5.00	5.25	1.68	0.00	55.13
BG C5 | 2.2.1	6.04	11.37	4.42	3.29	3.30	0.97	0.00	29.40
S90P10 | 2.2.2	8.05	15.16	11.42	9.00	16.62	3.01	0.00	63.27
S97T03 | 2.2.3	8.05	15.16	7.46	4.67	6.17	1.43	0.00	42.95
BG C5 - SS | 2.3.1	4.12	7.61	2.93	1.71	1.90	0.58	0.00	18.85
S90P10 - SS | 2.3.2	4.69	8.67	8.93	7.24	14.82	2.47	0.00	46.83
S90P10 | 2.3.3	4.44	8.22	8.83	8.02	15.26	2.57	0.00	47.33
S97T03 - SS | 2.3.4	4.69	8.67	4.97	2.91	4.37	0.90	0.00	26.51
S97T03 | 2.3.5	4.94	9.13	4.77	3.19	4.19	0.94	0.00	27.15

Figure 31. Functional unit upstream process contribution for global warming potential impact – Part 2.



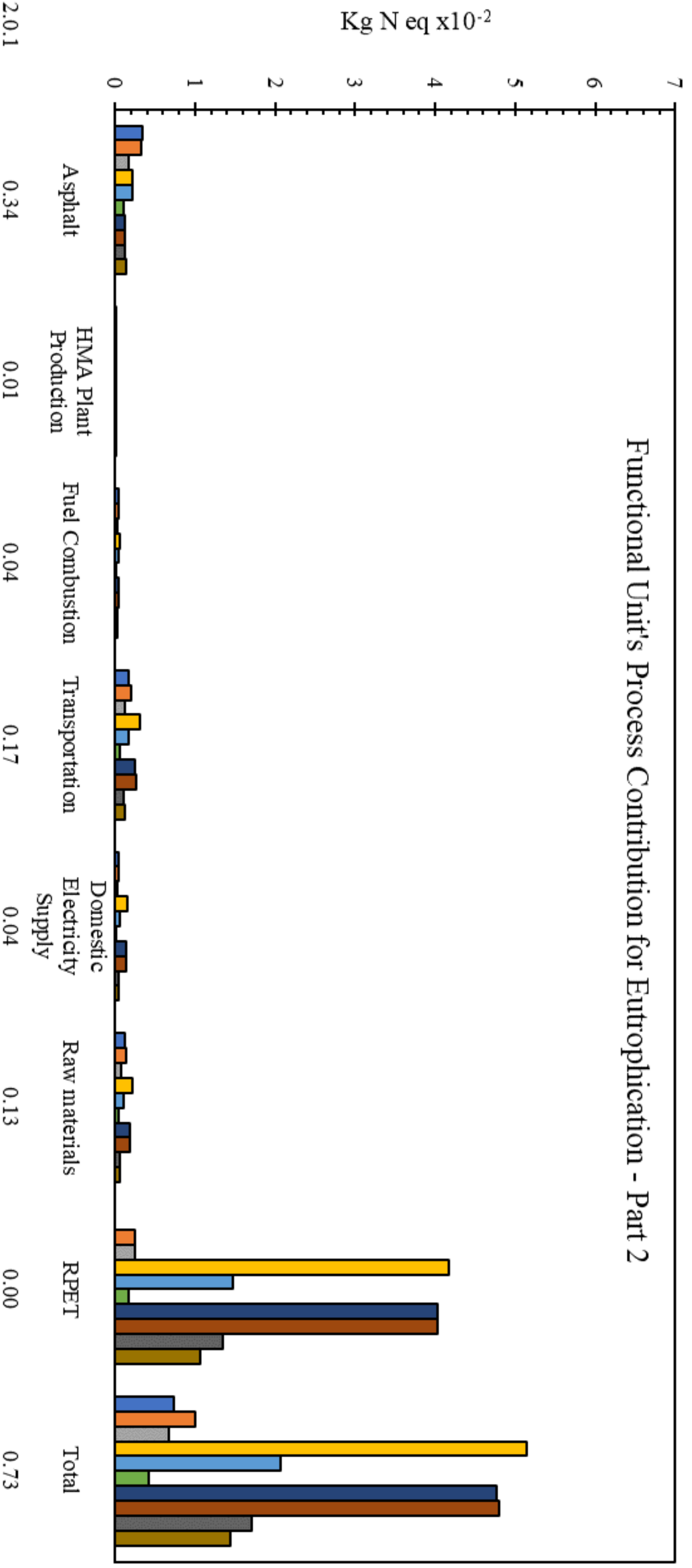
	Asphalt	HMA Plant Production	Fuel Combustion	Transportation	Domestic Electricity Supply	Raw materials	RPET	Total
BG C5 - SS | 2.4.1	3.99	7.52	2.90	1.69	1.88	0.57	0.00	18.56
S90P10 - SS | 2.4.2	4.55	8.57	8.89	7.22	14.80	2.46	0.00	46.50
S90P10 | 2.4.3	4.31	8.12	8.79	8.00	15.23	2.56	0.00	47.02
S97T03 - SS | 2.4.4	4.55	8.57	4.94	2.89	4.34	0.89	0.00	26.18
S97T03 | 2.4.5	4.55	8.57	4.56	3.10	4.08	0.90	0.00	25.77
BG C5 - SS | 2.5.1	6.06	11.41	5.06	3.14	4.50	1.10	0.00	31.28
BG C5 | 2.5.2	5.17	9.74	4.40	3.64	4.45	1.09	0.00	28.49
S90P10 | 2.5.3	7.60	14.30	11.97	9.74	18.61	3.27	0.00	65.49
S97T03 | 2.5.4	7.60	14.30	7.58	4.78	7.37	1.58	0.00	43.20

Figure 32. Functional unit upstream process contribution for global warming potential impact – Part 3.



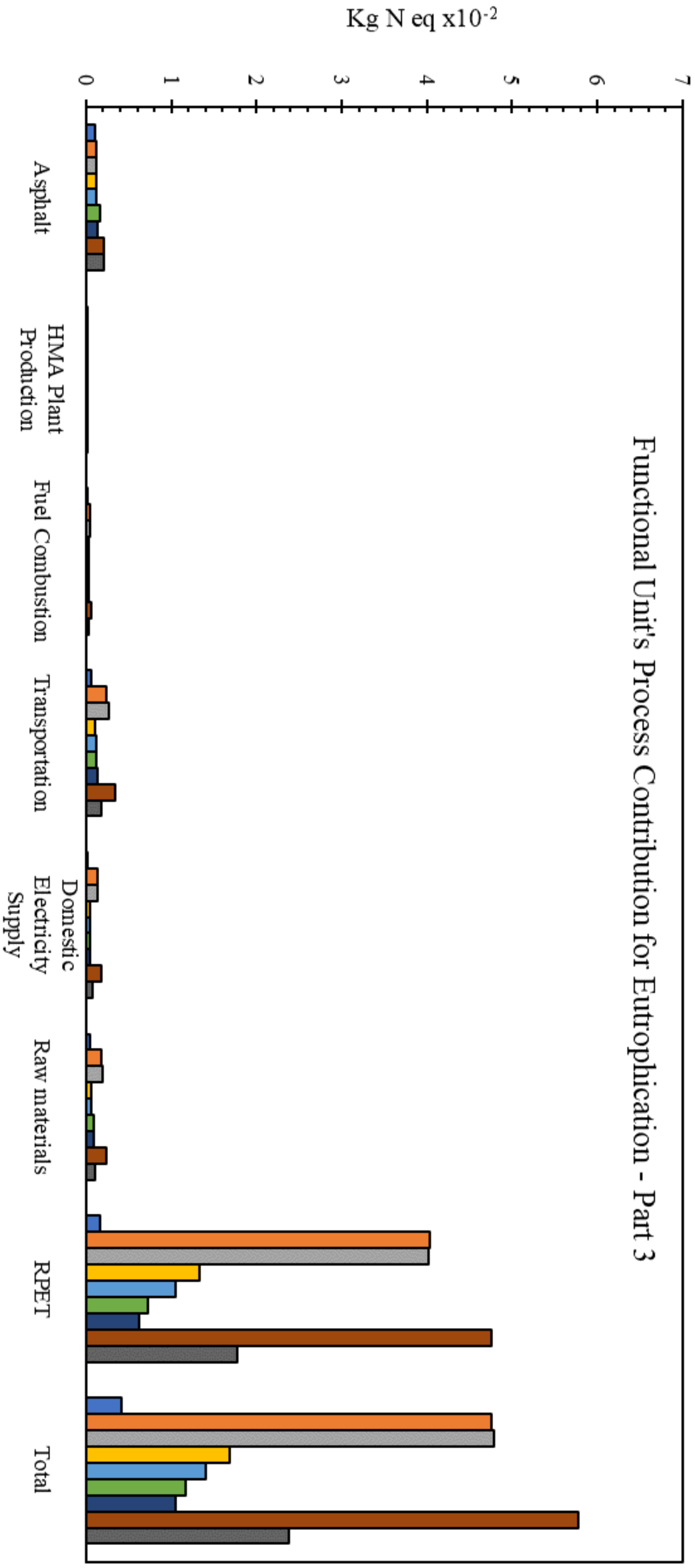
	Asphalt	HMA Plant Production	Fuel Combustion	Transportation	Domestic Electricity Supply	Raw materials	RPET	Total
BG C5 | 1.0.1	0.25	0.01	0.04	0.15	0.04	0.12	0.00	0.61
S97T03 | 1.0.2	0.26	0.01	0.05	0.18	0.06	0.13	1.15	1.84
BG C5 - SS | 1.1.1	0.13	0.01	0.02	0.05	0.03	0.07	0.26	0.57
BG C5 | 1.1.2	0.11	0.01	0.02	0.08	0.03	0.07	0.22	0.53
S90P10 | 1.1.3	0.16	0.01	0.05	0.26	0.15	0.22	4.17	5.02
S97T03 | 1.1.4	0.16	0.01	0.04	0.12	0.06	0.10	1.49	1.97
BG C5 - SS | 1.2.1	0.13	0.01	0.03	0.12	0.05	0.10	1.05	1.49
BG C5 | 1.2.2	0.11	0.01	0.03	0.14	0.05	0.10	0.88	1.30
S90P10 | 1.2.3	0.16	0.01	0.06	0.34	0.18	0.25	5.13	6.14
S97T03 | 1.2.4	0.17	0.01	0.04	0.20	0.09	0.14	2.47	3.11

Figure 33. Functional unit upstream process contribution for eutrophication impact. – Part 1.



	Asphalt	HMA Plant Production	Fuel Combustion	Transportation	Domestic Electricity Supply	Raw materials	RPET	Total
BG C5 | 2.0.1	0.34	0.01	0.04	0.17	0.04	0.13	0.00	0.73
BG C5 | 2.1.1	0.33	0.01	0.04	0.19	0.04	0.13	0.24	1.00
BG C5 | 2.2.1	0.16	0.01	0.02	0.12	0.03	0.08	0.24	0.66
S90P10 | 2.2.2	0.22	0.01	0.06	0.31	0.15	0.22	4.17	5.14
S97T03 | 2.2.3	0.22	0.01	0.04	0.17	0.06	0.10	1.48	2.07
BG C5 - SS | 2.3.1	0.11	0.00	0.02	0.07	0.02	0.04	0.16	0.42
S90P10 - SS | 2.3.2	0.13	0.01	0.04	0.25	0.14	0.18	4.03	4.77
S90P10 | 2.3.3	0.12	0.01	0.04	0.27	0.14	0.19	4.02	4.79
S97T03 - SS | 2.3.4	0.13	0.01	0.02	0.11	0.04	0.06	1.34	1.70
S97T03 | 2.3.5	0.13	0.01	0.02	0.12	0.04	0.06	1.06	1.44

Figure 34. Functional unit upstream process contribution for eutrophication impact. – Part 2.



	Asphalt	HMA Plant Production	Fuel Combustion	Transportation	Domestic Electricity Supply	Raw materials	RPET	Total
BG C5 - SS | 2.4.1	0.11	0.00	0.02	0.06	0.02	0.04	0.16	0.41
S90P10 - SS | 2.4.2	0.12	0.01	0.04	0.24	0.14	0.18	4.03	4.76
S90P10 | 2.4.3	0.12	0.01	0.04	0.27	0.14	0.19	4.02	4.78
S97T03 - SS | 2.4.4	0.12	0.01	0.02	0.10	0.04	0.06	1.34	1.69
S97T03 | 2.4.5	0.12	0.01	0.02	0.11	0.04	0.06	1.05	1.41
BG C5 - SS | 2.5.1	0.16	0.01	0.03	0.12	0.04	0.08	0.73	1.17
BG C5 | 2.5.2	0.14	0.01	0.02	0.13	0.04	0.09	0.62	1.05
S90P10 | 2.5.3	0.21	0.01	0.06	0.33	0.17	0.24	4.76	5.78
S97T03 | 2.5.4	0.21	0.01	0.04	0.17	0.07	0.11	1.78	2.38

Figure 35. Functional unit upstream process contribution for eutrophication impact. – Part 3.

4.2.3 FU's Environmental Score

Following the weighting criteria for the normalized FU results, which favors the global warming potential with a higher weight, the environmental score is graph by impact and total score. It is then interpreted in comparison with the conventional HMA mixes and pondered in percentage of environmental performance.

For the functional units with the HMA mixtures from Ferreira et al, (2022), presented in Figure 36, the conventional HMA alternative, FU 1.0.1 – M1.0 – BG C5 reports an ES value of 47.72. The functional unit with best environmental performance was the FU 1.1.2 – M1.1 – BG C5, with an ES value of 24.91, representing a reduction of – 47.79 % in pondered impacts.

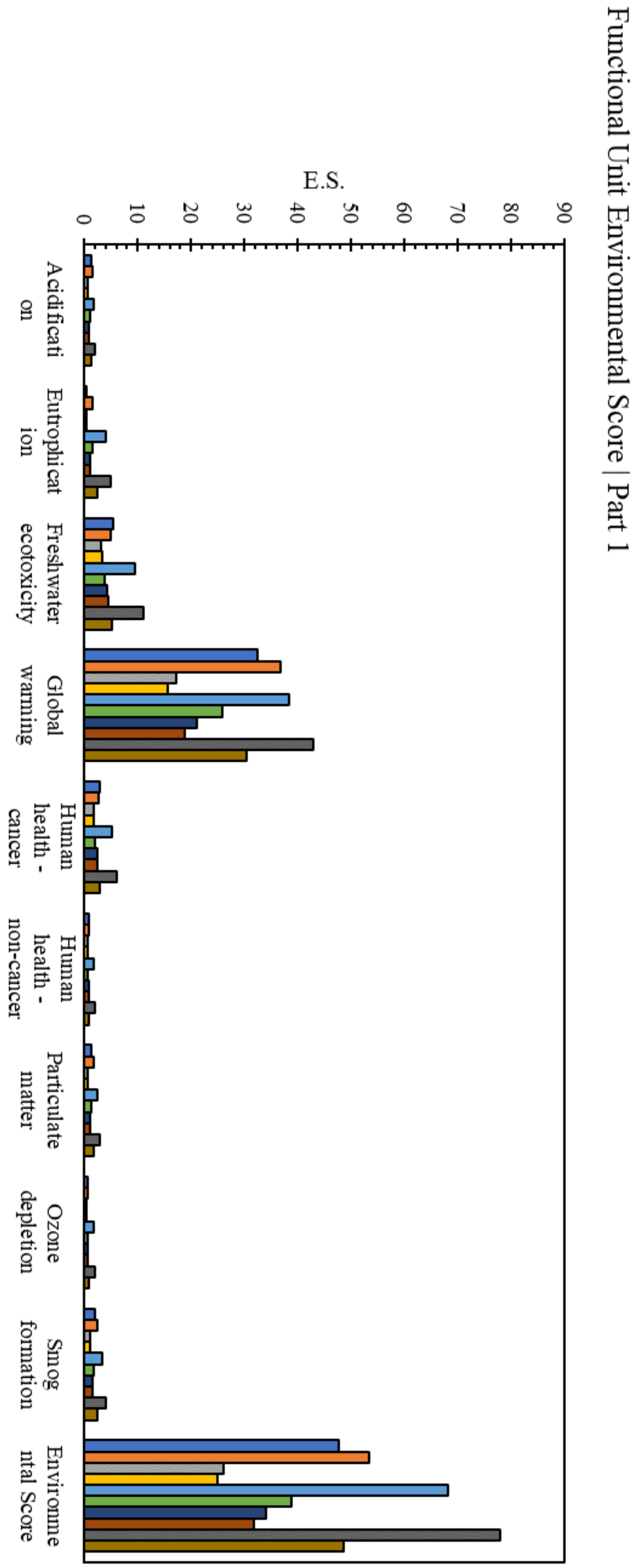
The functional unit with worst environmental performance was the FU 1.2.3 – M1.2 – S90P10, with an ES value of 78. It represents an increase of + 63.45 % in pondered impacts, in comparison with the conventional HMA mixture variant.

For the functional units with the HMA mixtures of Arao et al, (2017), presented in Figure 37 and Figure 38, the same analysis goes as follow. The conventional HMA alternative, FU 2.0.1 – M2.0 BG C5 reports an ES value of 51.85, slightly higher than FU 1.0.1, but under the same greatness level.

The functional unit with best environmental performance was the FU 2.4.1 – M2.4 – BG C5 SS, with an ES value of 17.90, representing a reduction of – 65.47% in pondered impacts.

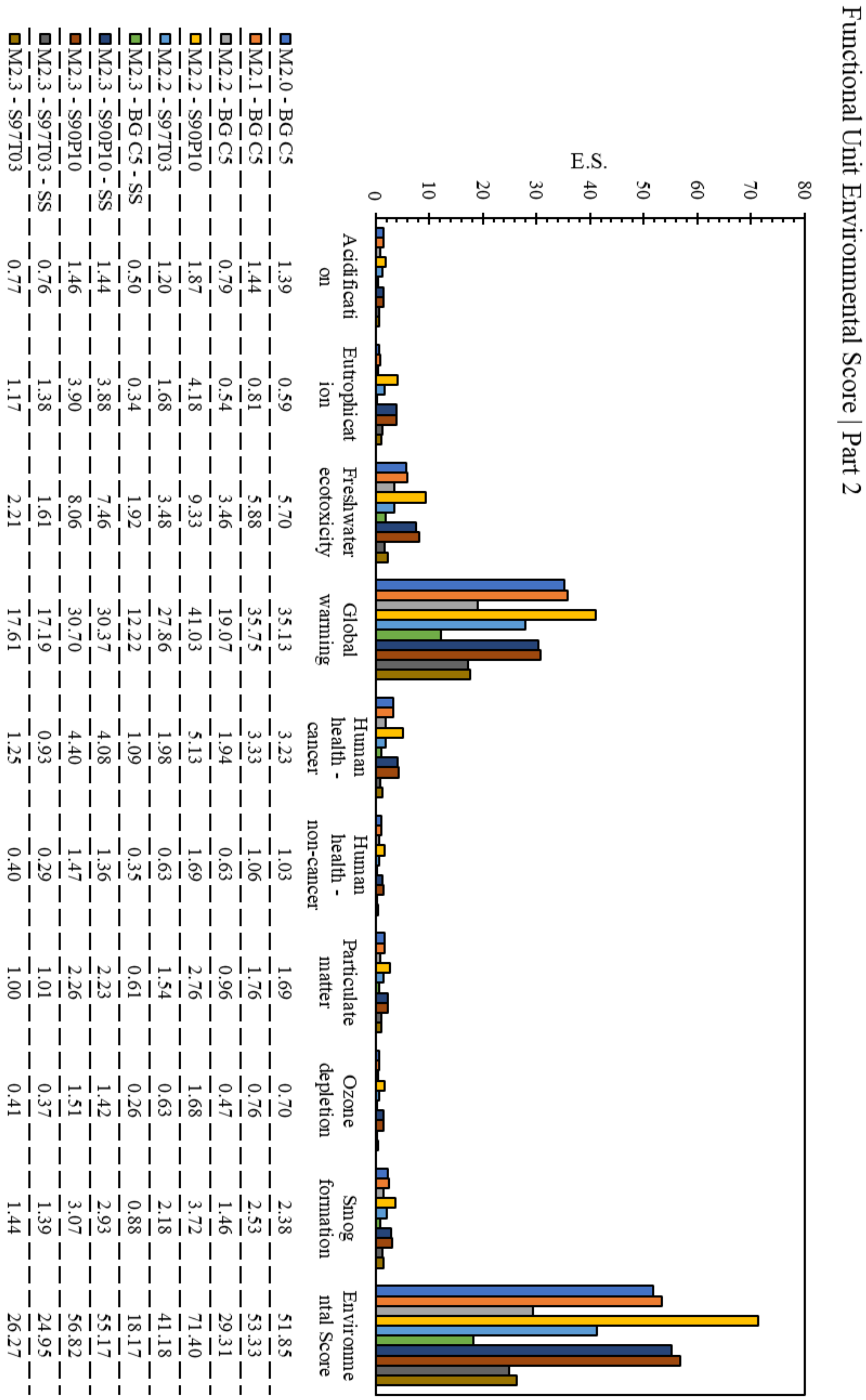
The functional unit with the worst environmental performance was the FU 2.5.3 – M2.5 – S90P10, with an ES value of 75.62, representing an increase of + 45.84% in pondered impacts in comparison with the conventional HMA mixture variant.

This result sets the ground for a sensibility analysis for RPET content in pavement structures, in which maximum sustainable limits could be set for RPET addition in HMA, considering its effects in the final mechanical parameters.



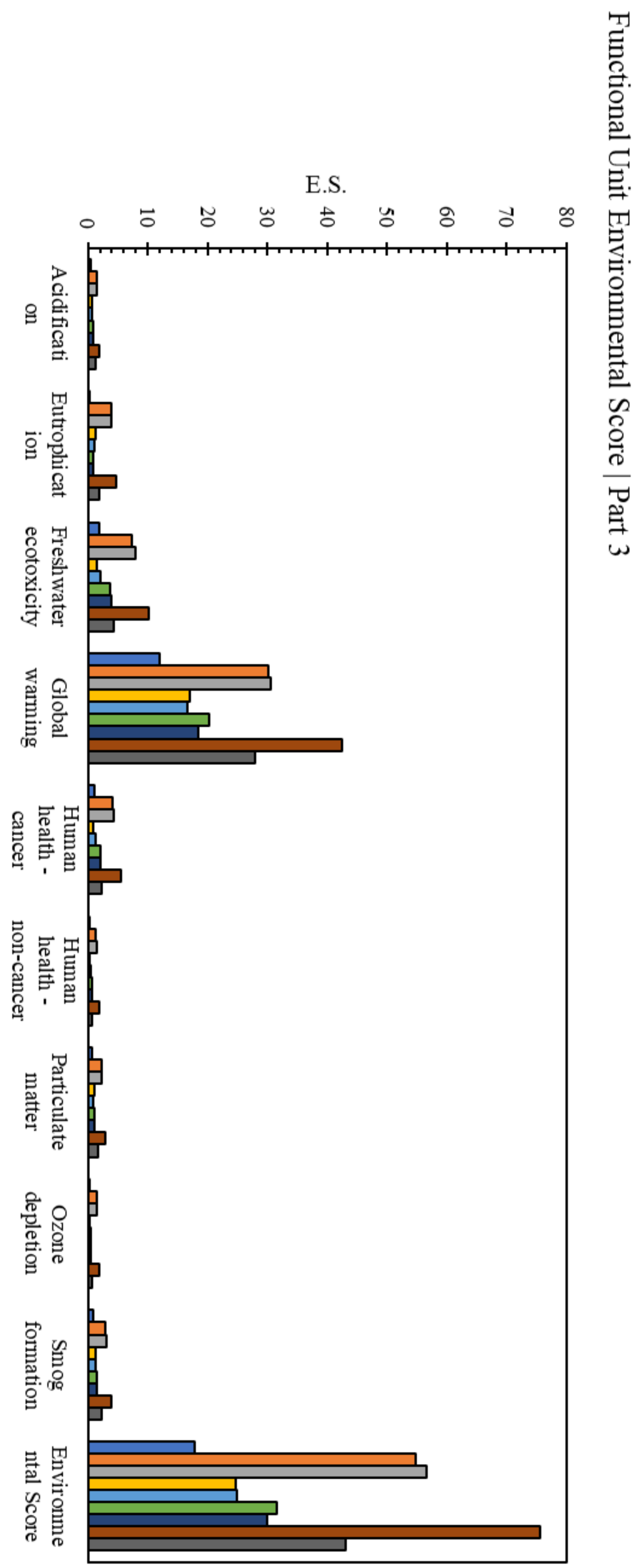
	Acidification	Eutrophication	Freshwater ecotoxicity	Global warming	Human health - cancer	Human health - non-cancer	Particulate matter	Ozone depletion	Smog formation	Environmental Score
M1.0 - BG C5	1.28	0.50	5.38	32.42	3.02	0.98	1.43	0.66	2.05	47.72
M1.0 - S97T03	1.52	1.50	4.88	36.80	2.75	0.88	1.79	0.75	2.48	53.35
M1.1 - BG C5 - SS	0.67	0.47	3.13	17.32	1.75	0.57	0.76	0.41	1.01	26.08
M1.1 - BG C5	0.62	0.43	3.42	15.69	1.89	0.62	0.72	0.45	1.07	24.91
M1.1 - S90P10	1.73	4.09	9.55	38.37	5.22	1.74	2.51	1.69	3.28	68.18
M1.1 - S97T03	1.08	1.61	3.80	25.85	2.13	0.69	1.32	0.65	1.77	38.91
M1.2 - BG C5 - SS	0.90	1.21	4.32	21.14	2.39	0.78	1.16	0.66	1.60	34.15
M1.2 - BG C5	0.81	1.06	4.42	18.93	2.43	0.80	1.06	0.66	1.56	31.74
M1.2 - S90P10	2.00	5.00	11.00	43.00	6.00	2.00	3.00	2.00	4.00	78.00
M1.2 - S97T03	1.35	2.53	5.25	30.36	2.91	0.95	1.81	0.96	2.50	48.62

Figure 36: Functional unit's environmental score – Part 1.



	Acidificati on	Eutrophicat ion	Freshwater ecotoxicity	Global warming	Human health - cancer	Human health - non-cancer	Particulate matter	Ozone depletion	Smog formation	Environme ntal Score
M2.0 - BG C5	1.39	0.59	5.70	35.13	3.23	1.03	1.69	0.70	2.38	51.85
M2.1 - BG C5	1.44	0.81	5.88	35.75	3.33	1.06	1.76	0.76	2.53	53.33
M2.2 - BG C5	0.79	0.54	3.46	19.07	1.94	0.63	0.96	0.47	1.46	29.31
M2.2 - S90P10	1.87	4.18	9.33	41.03	5.13	1.69	2.76	1.68	3.72	71.40
M2.2 - S97T03	1.20	1.68	3.48	27.86	1.98	0.63	1.54	0.63	2.18	41.18
M2.3 - BG C5 - SS	0.50	0.34	1.92	12.22	1.09	0.35	0.61	0.26	0.88	18.17
M2.3 - S90P10 - SS	1.44	3.88	7.46	30.37	4.08	1.36	2.23	1.42	2.93	55.17
M2.3 - S90P10	1.46	3.90	8.06	30.70	4.40	1.47	2.26	1.51	3.07	56.82
M2.3 - S97T03 - SS	0.76	1.38	1.61	17.19	0.93	0.29	1.01	0.37	1.39	24.95
M2.3 - S97T03	0.77	1.17	2.21	17.61	1.25	0.40	1.00	0.41	1.44	26.27

Figure 37: Functional unit's environmental score – Part 2.



	Acidification	Eutrophication	Freshwater ecotoxicity	Global warming	Human health - cancer	Human health - non-cancer	Particulate matter	Ozone depletion	Smog formation	Environmental Score
M2.4 - BG C5 - SS	0.49	0.34	1.89	12.04	1.07	0.34	0.60	0.26	0.87	17.90
M2.4 - S90P10 - SS	1.43	3.88	7.43	30.16	4.06	1.35	2.21	1.42	2.91	54.86
M2.4 - S90P10	1.45	3.90	8.04	30.49	4.38	1.46	2.25	1.50	3.06	56.53
M2.4 - S97T03 - SS	0.76	1.38	1.59	16.98	0.92	0.29	1.00	0.37	1.37	24.64
M2.4 - S97T03	0.73	1.15	2.10	16.71	1.19	0.38	0.95	0.40	1.38	24.99
M2.5 - BG C5 - SS	0.85	0.95	3.63	20.29	2.04	0.66	1.11	0.54	1.53	31.59
M2.5 - BG C5	0.78	0.85	3.89	18.48	2.16	0.70	1.02	0.57	1.53	29.97
M2.5 - S90P10	1.96	4.70	10.24	42.47	5.61	1.86	2.95	1.86	3.95	75.62
M2.5 - S97T03	1.22	1.94	4.22	28.01	2.37	0.76	1.63	0.75	2.23	43.13

Figure 38: Functional unit's environmental score – Part 3.

4.2.4 Sensitivity analysis

A sensibility analysis was developed to explore the tendency of the impact in global warming potential (GWP) and environmental score by the increase of RPET added in each functional unit. A Linear tendency was plotted for each set of functional units with the same HMA mix matrix for the surface course.

In Figure 39 is plotted the GWP of the FUs corresponding to Ferreira et al (2022) mixtures, by the net RPET mass in pavement structure, in Kg/m^2. The conventional HMA mix point is selected and projected horizontally and is intercepted by the linear tendency of the FUs by HMA matrix. The vertical projection of such intercept is defined as the equilibrium amount of RPET in which sustainability can be achieved, with a maximum value of approximately 23 Kg/m^2 of RPET present in the overall pavement structure.

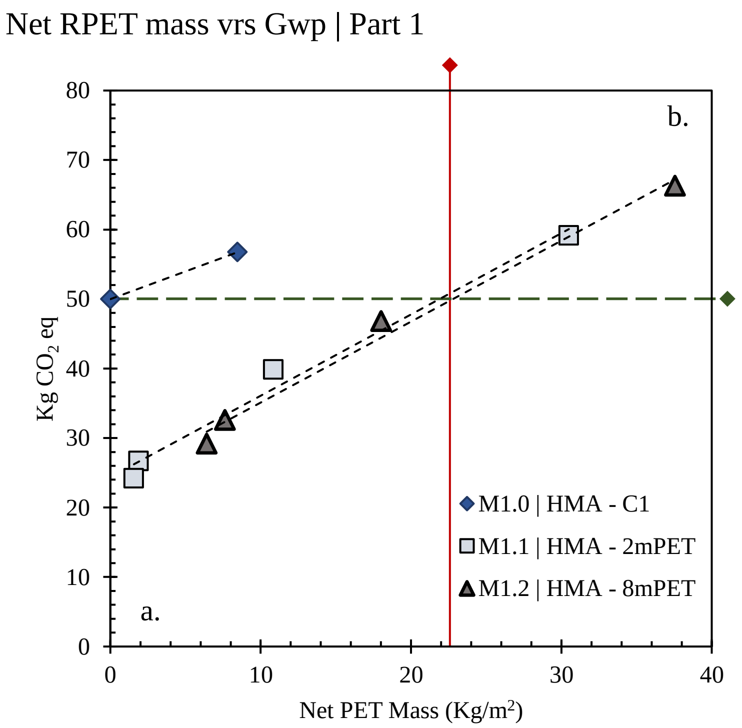


Figure 39: Sensibility analysis chart for net PET mass addition for each functional unit versus Global Warming Potential – Part 1.

In Figure 40, is plotted the GWP of the FUs corresponding to Arao et al (2017) mixtures, by the net RPET mass in pavement structure, in Kg/m^2. The conventional HMA mix point is selected and projected horizontally and is intercepted by the linear tendency of the FUs by HMA matrix. The vertical projection of such intercept is defined as the equilibrium amount of RPET in which sustainability can be achieved, with a maximum value of approximately 25 Kg/m^2 of RPET present in the overall pavement structure.

For both charts, areas "a" and "b" are subsequently identified by the two projected lines, with the following interpretation: area "a" corresponds to the sustainable pavement alternatives, with less impacts in greenhouse emissions in comparison with the conventional pavement without RPET addition; and area "b" that correspond to the unsustainable pavement alternatives with higher greenhouse emission amounts than a conventional pavement.

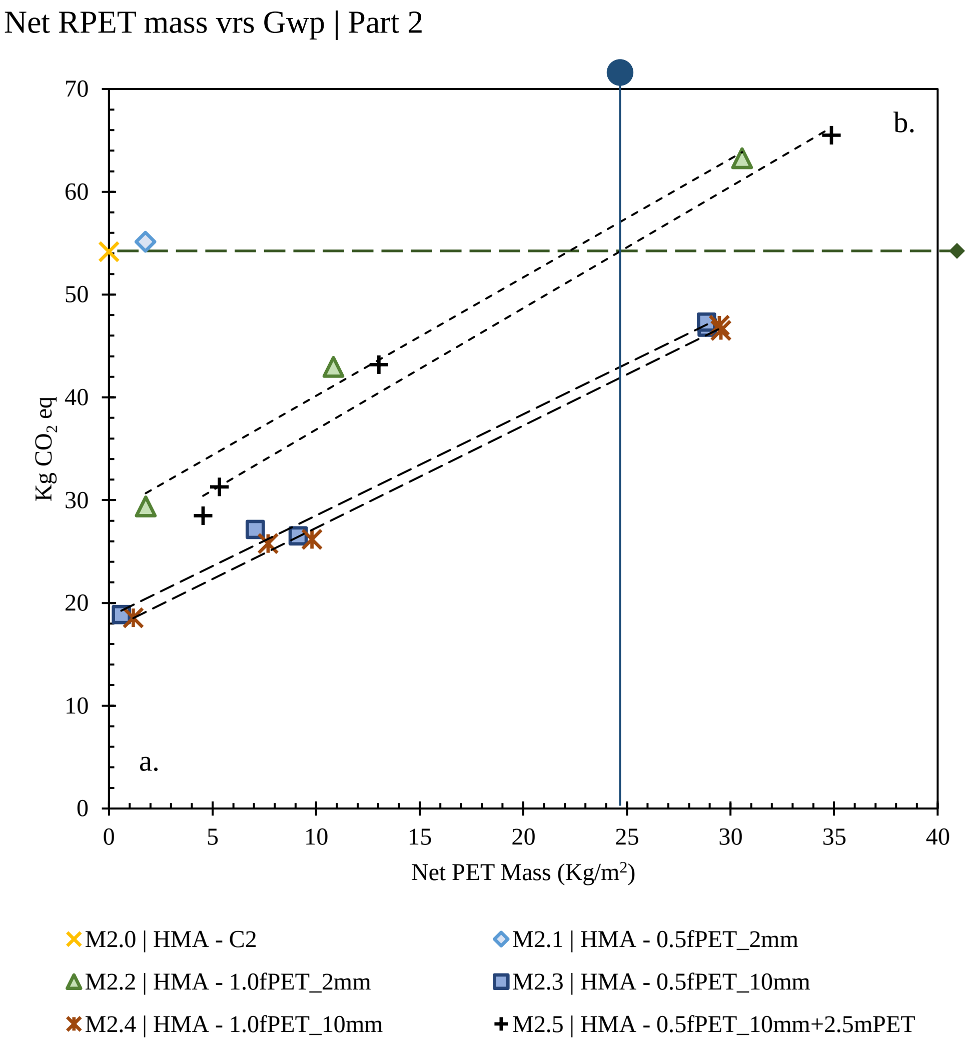


Figure 40: Sensibility analysis chart for net PET mass addition for each functional unit versus Global Warming Potential – Part 2.

The same linear pattern for all sets of functional units with each HMA mixtures is observed, with approximately the same slope value and proportionality. Such slope represents the sensibility of the GWP impact by the increase of net pet mass addition in pavement structures, and the offset of each tendency line represents the mechanical improvement that the RPET adds to the overall pavement structure, with the better overall mixtures being under and lower in the scale of the chart.

In Figure 41 is plotted the ES of the FUs corresponding to Ferreira et al (2022) mixtures, by the net RPET mass in pavement structure, in Kg/m^2. The conventional HMA mix point is selected and projected horizontally and is intercepted by the linear tendency of the FUs by HMA matrix. The vertical projection of such intercept is defined as the equilibrium amount of RPET in which sustainability can be achieved, with a maximum value of approximately 17.5 Kg/m^2 of RPET present in the overall pavement structure.

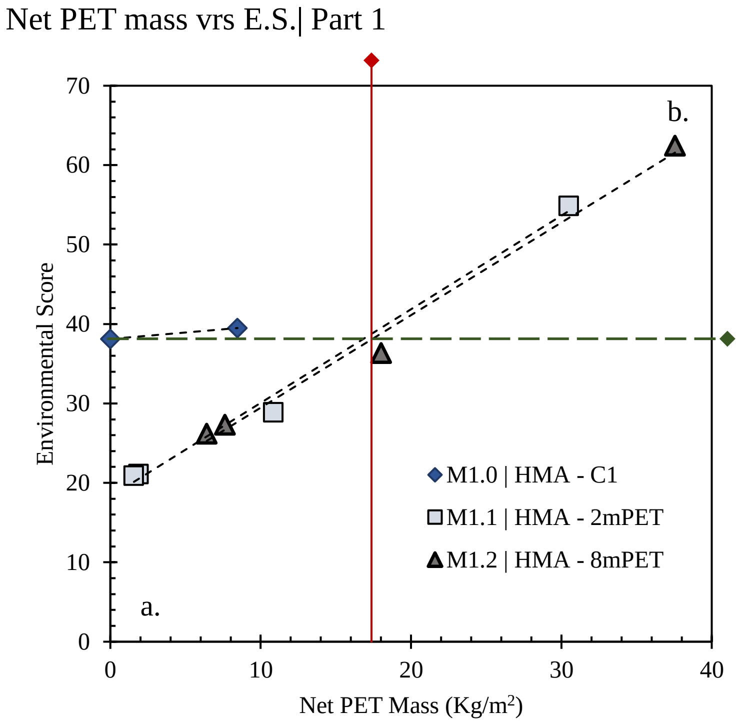


Figure 41: Sensibility analysis chart for net PET mass addition for each functional unit versus Environmental Score – Part 1.

In Figure 42 is plotted the ES of the FUs corresponding to Arao et al (2017) mixtures, by the net RPET mass in pavement structure, in Kg/m^2. The conventional HMA mix point is selected and projected horizontally and is intercepted by the linear tendency of the FUs by HMA matrix. The vertical projection of such intercept is defined as the equilibrium amount of RPET in which sustainability can be achieved, with a maximum value of approximately 27.5 Kg/m^2 of RPET present in the overall pavement structure.

For both charts, areas “a” and “b” are also subsequently identified by the two projected lines, with the following interpretation: area “a” corresponds to the sustainable pavement alternatives, with less impacts in greenhouse emissions in comparison with the conventional pavement without RPET addition; and area “b” that correspond to the unsustainable pavement alternatives with higher greenhouse emission amounts than a conventional pavement. It can also be considered that the environmental score ponders all characterized environmental impacts into one numerical score, which by itself can be more valuable for stakeholders.

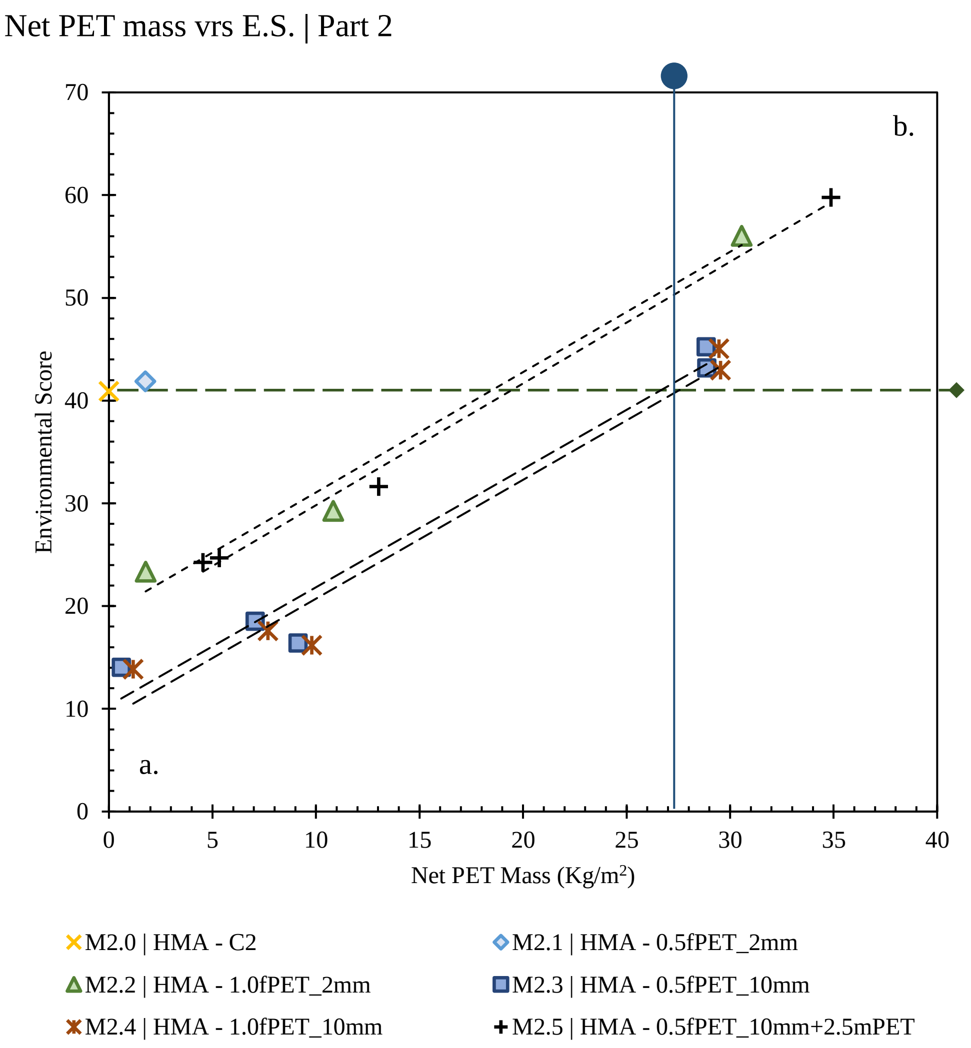


Figure 42: Sensibility analysis chart for net PET mass addition for each functional unit versus Environmental Score – Part 2.

The same linear pattern for all sets of functional units with each HMA mixtures is observed, with approximately the same slope value and proportionality. Such slope represents the sensibility of the GWP impact by the increase of net pet mass addition in pavement structures, and the offset of each tendency line represents the mechanical improvement that the RPET adds to the overall pavement structure, with the better overall mixtures being under and lower in the scale of the chart.

5 DISCUSSION

The key to present LCA results and to interpret them with ease is transparency in decisions and considerations made during the scope definition, data quality and validation for the LCI. The data analysis performed in the present study was be summarized in refinement layers, with the bulk LCIA results presented in bar chart; then an internal normalization criterion was adopted for relative comparison between declared and functional units. Subsequently, the weighting criteria was applied for single environmental score assignation, and lastly, sensibility analysis was applied relating two variables into meaningful interpretation. Fair consideration on the characterized environmental impacts from the LCIA is also required. In that context, some of the key considerations are as follow.

The declared unit's LCA takes as the system's boundary the production of one ton of HMA as the comparative representative unit. The importance of this analysis perspective is to compare such production without considering each mix's functional parameters and serving as a standpoint for any asphalt concrete production facility for their own environmental product declaration. Under the same upstream input and output conditions, a conventional HMA mix presents better overall environmental performance and wastes than a HMA with RPET added in aggregate substitution, through the "dry" process. Such results are synthesized in Table 12.

Table 12. Synthesis of GWP and ES values and comparison for declared units.

Author	ID	Description	GWP		ES	
			Kg CO_2 eq	%*	value	%*
Ferreira et al, (2022)	M1.0	Conventional HMA mix 1	129.16	-	50.77	-
	M1.2	Maximum Result	169.30	31.08%	78.00	53.63%
Arao et al, (2017)	M2.0	Conventional HMA mix 2	139.49	-	55.19	-
	M2.5	Maximum Result	165.04	18.32%	71.92	30.31%

*Percentage relative comparison of each DU with the conventional HMA mix results for each author.

The functional unit's LCA expands the system's boundary up to the construction phase, proposing a variety pavement structures with the same functional qualities for traffic demand and durability. The variant pavement structures with HMA + RPET mixes were considered in the design software procedure to evaluate the sensitivity of such mixes to a variance in layer stiffness. Considering the better mechanical properties and overall functional performance of the HMA + RPET mixes for the surface course, the functional unit comparison resulted in savings in almost all environmental impact categories for each square meter of pavement constructed and ready to use, with an overall layer thickness optimization effect that carries a cascade of upstream resource and emissions savings. This effect was furthermore explored with the sensibility analysis of net PET mass added by FU, with an equilibrium mass identified for global warming potential and environmental score, stablishing the ground for the sustainable pavement definition and delimitation. Such results are synthesized in Table 13.

Table 13. Synthesis of GWP and ES values and comparison for functional units.

Author	ID	Description	GWP		ES	
			Kg CO2 eq	%*	value	%*
Ferreira et al, (2022)	FU 1.0.1	Conventional HMA mix 1	49.98	-	47.72	-
	FU 1.1.2	Best environmental Performance	24.19	-51.60%	24.91	-47.80%
	FU 1.2.3	Worst environmental Performance	66.30	32.65%	78.00	63.45%
Arao et al, (2017)	FU 2.0.1	Conventional HMA mix 1	54.17	-	51.85	-
	FU 2.4.1	Best environmental Performance	18.56	-65.74%	17.90	-65.48%
	FU 2.5.3	Worst environmental Performance	65.49	20.90%	75.62	45.84%

*Percentage relative comparison of each DU with the conventional HMA mix results for each author.

The sensitivity analysis performed to both declared and functional units was developed to explore the tendency of the impact in global warming potential (GWP) and environmental score by the increase of RPET added. It stablishes a novel sustainability criterion for pavement structures with addition of plastic post-consumer, in which integrates the mechanical and environmental performance, and allows for guidance in future plastic-pavement research. In Table 14 are synthesized the maximum quantity of net PET mass per square meter of pavement for each HMA mixture to maintain sustainability in comparison with conventional pavements. Based such criteria, the best HMA mixtures were the M2.3 and M2.4, with 0.5% and 1.0% of mass addition of 10 mm nominal size recycled post-consumer PET flakes.

Table 14. Synthesis of net PET mass sustainability limit for each HMA mixture pavement alternative.

Author	ID	Description	net PET mass (Kg/m^2)	
			vs. GWP	vs. ES
Ferreira et al, (2022)	M1.0	HMA - C1	0	0
	M1.1	HMA - 2mPET	22	17.5
	M1.2	HMA - 8mPET	23	17.5
Arao, Mieka (2017)	M2.0	HMA - C2	0	0
	M2.1	HMA - 0.5fPET_2mm	0	0
	M2.2	HMA - 1.0fPET_2mm	22	18
	M2.3*	HMA - 0.5fPET_10mm	34	26
	M2.4*	HMA - 1.0fPET_10mm	36	27.5
	M2.5	HMA - 0.5fPET_10mm+2.5mPET	25	19

*Net PET mass was extrapolated from tendency lines

These results agree with the literature when comparing a single impact category within LCA studies with a similar scope. Table 15 and Figure 43 present the comparison of global warming potential score for 1 m2 of different asphalt pavement structures using waste materials such as recycled polymer, crumb rubber, and reclaimed asphalt pavement (RAP), in contrast with the functional units of this study. Differences in system boundaries materials, data quality, and technical and temporal context may prevent a direct linear comparison rule but allows for validation of the LCIA results as they fit within the same order of magnitude.

Table 15. Global warming potential score of the different asphalt pavement structures considered in this study compared to the scores reported by the existing literature on the LCA of the use of waste materials.

Ref.	**ID**	**Description**	**Layer Thickness (cm)** Surface Course	Binder layer	Base layer	**GWP** (Kg CO_2 eq / m2)	**Life cycle phases considered**
This study	FU 1.0.1	M1.0 - BG C5	14.4		20	49.98	Pavement construction
	FU 1.1.2	M1.1 - BG C5	6.2		20	24.19	
	FU 1.2.3	M1.2 - S90P10	9.2		20	66.30	
	FU 2.0.1	M2.0 - BG C5	15		22	54.17	
	FU 2.4.1	M2.4 - BG C5 - SS	5		15	18.56	
	FU 2.5.3	M2.5 - S90P10	9.4		20	65.49	
Oreto et al, (2021)	W(HMA); Bi(HMA); Ba(HMA)	Conventional HMA pavement	4	5	20	63.58	
	W(HMA); Bi(HMA_PMB); Ba(HMA)	Modified HMA binder layer with RP in "wet" process				64.52	
	W(HMA); Bi(HMA_PMA); Ba(HMA)	Modified HMA binder layer with RP in "dry" process				63.79	
Farina et al, (2017)	S	Standard Pavement	5			43.37	Pavement construction and maintenance
	Wg	Rubberized gap-graded mixture	3			24.11	
	Wgr	Rubberized gap-graded mixture with RAP	3			23.26	

Key: HMA—hot mix asphalt; RP—recycled polymer; W—wearing course; Bi—binder layer; Ba-base; S—standard HMA structure; Wg—rubberized gap-graded mixture; Wgr—rubberized gap-graded mixture with RAP

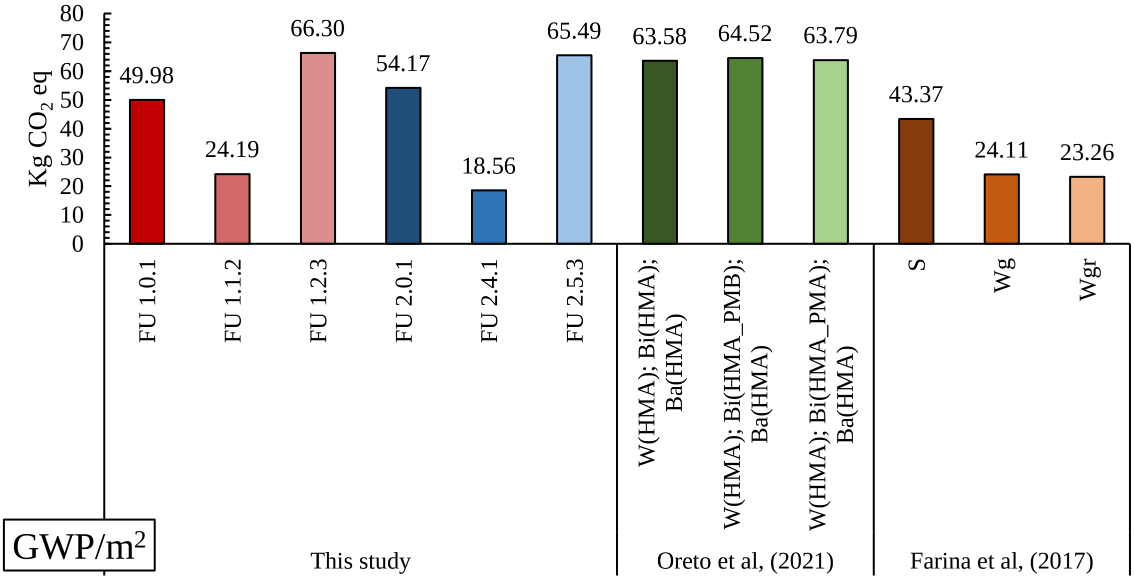


Figure 43. GWP score comparison for different asphalt pavement structures considered in this study in comparison to the scores reported by the existing literature on the LCA with use of waste materials in pavement structures.

5.1 Limitations and Challenges

The limitations and challenges for the present study are the following:

- Allocation criteria and circular economy of RPET. A cut-off rule was applied for the RPET to avoid a double counting on environmental savings, considering only the reclamation activities, from recollection of plastic waste, sorting, cleaning, grinding, and milling. Such processes imply a possible downcycling of the material. Although the current market for reclamation of RPET aims for a second life as resin ready-to-bottle, competing in quality with virgin resin, the use of the RPET as a pavement material may not have a market acceptance, as it will not have the same residual value for reclamation activities. The value of reclaimed asphalt with RPET inclusion and the potential environmental impacts that such reclamation may carry (Santos et al., 2021) are currently unknown. This same situation puts the assumption of the material being "on-demand" for the project in risk.
- Operation phase. Due to the novelty of the use of RPET in asphalt mixtures, the environmental impacts that will carry during the operation phase are currently uncertain, with concerns for generation of micro or nano plastics (MP and NP) due to surface wearing or health hazards for workers during pavement reclamation and recycling (Santos et al., 2021). Studies have been developed on the nano plastics generation potential, but it has proven to be difficult to evaluate the release of MPs on real roads, due to the number of external variables and lack of specialized essays (Enfrin et al., 2022).
- Dependence on secondary data, data quality, and availability. The quality of an LCA study depends on the data used, the source, and quality seal. The use of secondary data is implemented to fill the gaps on primary data on the subject, the location, and established systems boundaries. The present study relies on the secondary data provided in public databases and may carry internal errors that are periodically addressed. To assess the data quality for the main processes in the present LCA, the data were revised and checked on each respective original source and reference.
- Pavement design methodology. The pavement design methodology implements a mechanistic–empirical approach for an elastic multilayer case. Calibrations and optimizations on the software for the studied materials may results in pavement structures that may differ with those currently obtained for the present LCA but will not change the overall environmental savings tendency obtained.

6 CONCLUSION AND RECOMMENDATIONS

The proposal of new construction materials or new composites for civil construction or pavements should be assessed for their life-cycle environmental impacts, alongside their transport-related mechanical and functional parameters. This is due to the non-triviality of the environmental performance of any new material, as it can have a strong upstream cascade effect for any impact category. The LCA methodology demands the analyst establish a closed system boundary and conditions, making any LCA results subject to interpretation and subsequent adaptations for any real-life project proposal.

The present study marks a standpoint for pavement researchers on new sustainable materials, as it sustains the hypothesis of the RPET as a promising HMA optimizer. It stablishes a novel sustainability criterion for pavement structures with addition of plastic post-consumer, in which integrates the mechanical and environmental performance, and allows for guidance in future plastic-pavement research. The following conclusions can be detailed.

1. A comprehensive life-cycle assessment was defined for the sustainable pavement alternatives with Hot Mix Asphalt mixtures with addition of recycled post-consumer polyethylene terephthalate, with the use of primary data and adapted to a Brazilian context.
2. Data gaps were filled with secondary data from public-access pavement-oriented life-cycle inventory databases, environmental product declaration for key product processes, literature review in scientific databases and adapting the Brazilian domestic electricity supply matrix.
3. Functional unit definition was performed using the National Design Methodology MeDiNa for pavement structure design, with consideration of mechanical and performance parameters for each HMA mixture, traffic condition representative of a medium-traffic primary arterial road system and a 10-year analysis period design.
4. Environmental impacts were successfully characterized and assessed by the tool for the reduction and assessment of chemical and other environmental impacts “TRACI 2.0”, including ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, human health criteria-related effects, human health cancer, human health noncancer and ecotoxicity.
5. Internal normalization and weighting for single environmental score criterion was applied for the declared and functional units, in accordance with the life-cycle

assessment ISO normative and stakeholder perspective. It allows for a better decision-making process, comparative analysis and easy comprehension of results.

6. A sensitivity analysis was performed to explore the tendency of the impact in global warming potential (GWP) and environmental score by the increase of RPET added in each declared and functional unit. It allows for easy sustainability metric assessment of pavement with alternative materials, particularly recycled post-consumer plastics.
7. Lastly, comparison was made with LCA studies with similar scope, finding good affinity between pavement structures, technologies implemented, primary and secondary data used and local considerations. Differences in system boundaries materials, data quality, and technical and temporal context may prevent a direct linear comparison rule but allows for validation of the LCIA results as they fit within the same order of magnitude.

For every single square meter of sustainable pavement constructed with HMA + RPET and taking a mass of 57 g for each PET bottle discarded, it represents usage of an equivalent of approximately 87 PET bottles. For a 1 km, two lane (7.00 m wide) roadway paved with these sustainable mixes, it represents 34.713 t of RPET, equivalent to 609,000 discarded PET bottles. On the other hand, the sensibility analysis proposes a sustainability limit of up to 36 Kg of net PET mass per square meter o pavement developed with recycled post-consumer PET. It can significate the complete disposal of the total amount of post-consumer PET disposed in Brazil, up to 637,000 tons in 2021, on the construction of a total length of 2,527 Km of sustainable pavement, accounting with the same impact as a conventional pavement.

Based on the results and discussions of this study, the following key recommendations are proposed:

- System expansion, temporal analysis, and consideration of the operation phase will support the sustainable pavement hypothesis. It would require durability essays, fatigue and real scale experimental traffic simulator, in order to assess the RPET effect in sustainable pavements. It would also require the account of emissions and residues generated during the use phase, maintenance, and end-of-life recyclability of the pavements.
- A consequential LCA approach is recommended to assess the market response and effects of the RPET new lifecycle and destination. Such analysis would support the feasibility of the use of such recycled material, as it is considered a sub-product without

current direct large-scale demand. It can also explore the infrastructure and industry capabilities of Brazilian economy to sustain the implementation of this new technology and can indicate future challenges and sustainability metrics.

- Explore the expansion of public Brazilian databases for infrastructure and construction Life Cycle Assessment studies, focused on new materials and technologies, with continuous detail refinement for resources, emissions, and residues. Databases like the Work-Costs Reference System (SICRO from the National Department for Infrastructure and Transport (DNIT) are ideal frameworks for LCA dataset expansion and compilation.
- Validation of secondary data used on the present study, with careful adaptation to the local conditions of the Brazilian market and engineering practice.

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