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King Abdullah Petroleum Studies and Research Center

# Life Cycle Assessment (LCA) Framework for Examining the Environmental Impacts of Asphalt Pavement Mixtures in Saudi Arabia


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## About KAPSARC

KAPSARC is an advisory think tank within global energy economics and sustainability providing advisory services to entities and authorities in the Saudi energy sector to advance Saudi Arabia's energy sector and inform global policies through evidence-based advice and applied research.

*This publication is also available in Arabic.*

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# Key Points

Life cycle assessment (LCA) is the predominant approach for evaluating the environmental impacts of asphalt pavement.

A comprehensive LCA framework for assessing the environmental impacts of asphalt pavements in Saudi Arabia was defined. This model framework presents a clear approach for estimating the emissions generated from mix production in the cradle-to-gate state.

Energy consumption and transport distance (i.e., the distance between raw material production facilities and asphalt plants) are two of the main factors that need to be considered in estimations of greenhouse gas (GHG) emissions of asphalt pavements.

Several environmental impact categories, including stratospheric ozone depletion, photochemical ozone formation, acidification, eutrophication, climate change, and particulate matter formation, were identified.

The use of high recycled asphalt pavement (RAP) in asphalt mixtures led to a reduction in emissions (20% reduction in the case of the global warming potential (GWP) for the use of 35% RAP). Notably, these calculations were for a cradle-to-gate analysis.

This research highlights the importance of considering both direct and indirect emissions throughout the life cycle stages of asphalt pavements (cradle-to-gate), including raw material extraction, transportation, and asphalt production. Other stages of road construction, maintenance, and end-of-life phases can also be considered. The potential environmental benefits of optimizing asphalt pavement design and maintenance practices include lower energy consumption, emissions, and resource depletion.

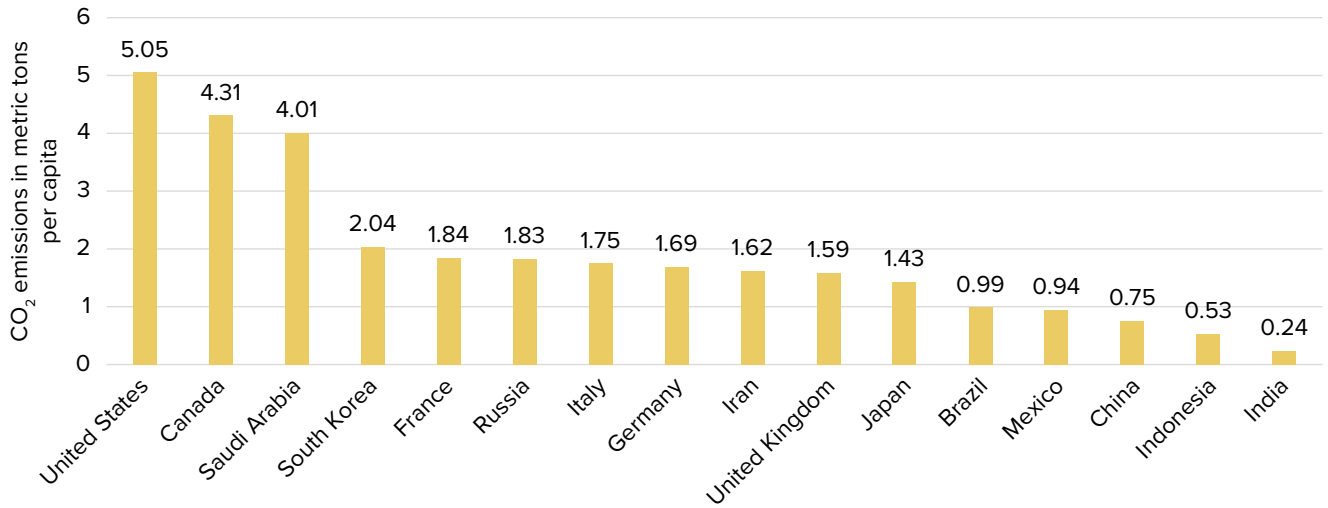
# Background and Motivation

As a core element of Saudi Vision 2030, sustainability is crucial, as the nation strives for net zero GHG emissions (CDMDNA 2023). The Kingdom of Saudi Arabia (KSA) is leading the way in addressing energy and climate concerns through innovative strategies such as the circular carbon economy (CCE), underscoring its commitment to clean energy and sustainable practices (Vision 2030 2024).

In KSA, the achievement of national climate change reduction goals is crucial. On October 23, 2021, the Saudi Arabian government updated its Nationally Determined Contributions (NDCs) under the Paris Agreement, significantly raising its annual emissions reduction target from 130 to 278 million tons of $CO_2$ equivalent (MtCO2-eq). This adjustment sets a new benchmark for total GHG emissions across all sectors to achieve a 45% reduction by 2030 (UNFCCC 2021) compared with 2019 levels. Among these sectors, the transportation sector plays a critical role in this ambitious move toward carbon neutrality. Saudi Arabia has the third highest road transportation emissions per capita in the world. In 2023, the average per capita transportation emissions in KSA were 4.01 metric tons[1] of $CO_2$ (see Figure 1; Statistica 2024).

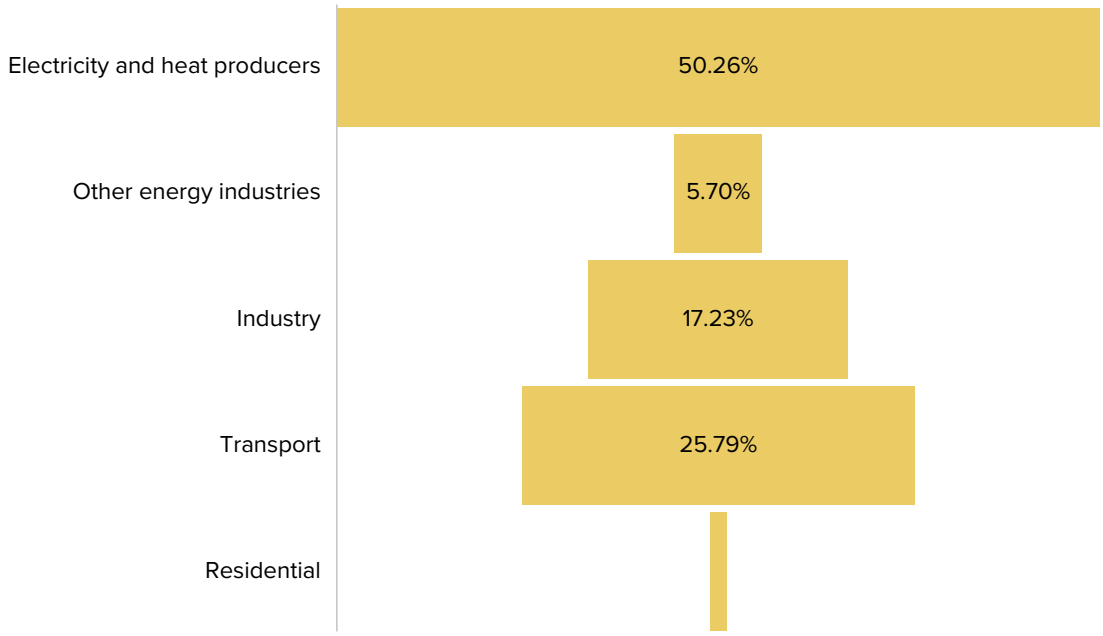
Fuel combustion is the leading source of GHG emissions, with $CO_2$ being the most significant contributor. In KSA, the power generation sector is responsible for the largest portion, accounting for 50.26% of total emissions. This is followed by the transport sector at 25.8% and the industrial sector at 17.23% (IEA 2022), as shown in Figure 2. Given the pressing climate emergency and the nation's commitment to achieving net-zero emissions, the decarbonization of the transportation sector must be expedited. Specifically, emissions from land transport should be decreased, as this sector accounts for a significant portion (approximately 26%) of total transportation emissions.

**Figure 1.** Per capita $CO_2$ emissions of the transportation sector worldwide in 2023.




Source: Statista (2024).

**Figure 2.** $CO_2$ output by sector in 2021.




Source: IEA (2022).

Many countries, including the United States, European nations, and the United Kingdom, are actively working toward attaining net-zero emissions in transportation. The strategies employed by these countries include increasing the adoption of electric vehicles, restricting the use of fossil fuel-powered cars, developing fuel economy standards for both light- and heavy-duty vehicles, investing in public transportation infrastructure, and embracing sustainable technologies alongside lower-carbon fuels (DOT 2024; DfT 2021; ITF 2023). Additionally, these countries are focusing on decarbonizing transportation infrastructure, such as road pavements. Several countries have also set ambitious targets to reduce emissions in asphalt mixtures as part of their broader climate goals. These targets focus on minimizing carbon emissions during the production and use of asphalt in road construction; examples are outlined in Table 1.

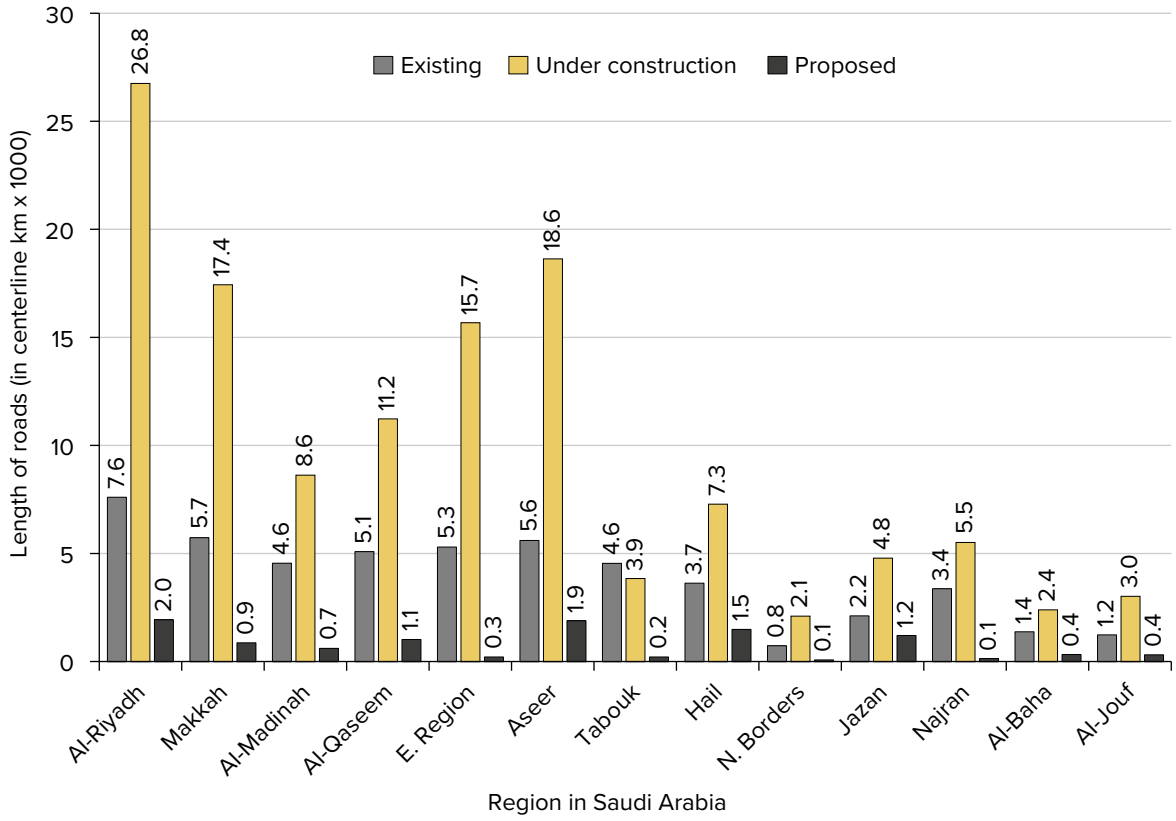
Like the counties mentioned in Table 1, KSA aims to reduce emissions. Focusing on sustainable road construction is crucial for meeting the country's goal of the net-zero emissions initiative. This includes promoting materials with lower carbon footprints, such as recycled asphalt pavement (RAP). Saudi Arabia boasts a large road network of more than 200,000 kilometers, including 66,000 kilometers of highways that connect major cities and neighboring countries and provide crucial links to airports, railways, and ports (LC 2019). The country also has an extensive municipal and urban roadway network that can be grouped as roads that already exist, are under construction, and are planned for future construction (Figure 3; GASTAT 2023). These roads are predominantly constructed with hot mix asphalt (HMA). Since the KSA has a large roadway network and plans for ambitious megaprojects (Oxborrow 2023), which are characterized by extensive infrastructure development, a significant

**Table 1.** Examples of asphalt material decarbonization efforts around the world.

| Country/Region | Initiative description | Source |
|---|---|---|
| United Kingdom | Net Zero concept scheme for asphalt: Integrating low-carbon technologies in asphalt production and use, aligning with the UK's overall Net Zero 2050 target. | National Highways in UK[2] |
| Europe | A Decarbonization Roadmap for the Asphalt Industry in Europe: Develop a roadmap and solutions to decarbonize the asphalt pavement (such as warm mix asphalt, recycled materials) in Europe in accordance with the European decarbonization objectives. | European Asphalt Pavement Association[3] |
| Australia | Australian Flexible Pavement Association (AfPA) Commitment to Net Zero. Develop pathways to reduce emissions from road asphalt construction activities. | Australian Flexible Pavement Association[4] |
| United States | A vison for Net Zero carbon emissions during asphalt production and construction by 2050 through promoting sustainable asphalt production and construction by reducing emissions through alternative fuels, advanced technologies (such as warm mix asphalt), and recycled asphalt pavement. | National Asphalt Pavement Association (NAPA)[5] |

demand for virgin materials, particularly for the construction of roads, has arisen. While these projects are instrumental in fostering economic growth and modernization, the extensive use of virgin materials raises concerns about heightened energy and resource consumption. Thus, the degree of emissions generated due to asphalt roadway construction in KSA must be understood, and different strategies for reducing GHG emissions from road construction activities must be evaluated. Most of the carbon footprint associated with asphalt mixtures is linked to the production of raw materials and their transportation, as well as the production of HMA and its transportation to construction sites, which highlights the need for materials with lower carbon footprints, such as mixes produced via RAP. Thus, research is needed to better understand road pavement structures and their environmental impacts via life cycle assessment (LCA). To the best of the authors' knowledge, to date, no LCA has been conducted on asphalt mixtures in KSA, and this study constitutes the first of those assessments in the country. This research also informs sustainable road construction practices and aligns with the national goals of the National Development Plan in Saudi Vision 2030, fostering resilient and environmental infrastructure by promoting the use of sustainable materials and practices (Shaukat 2024).

**Figure 3.** Infrastructure in Saudi Arabia: Existing, under construction, and proposed.




Source: GASTAT (2024). These road networks include both paved surfaces and lighting.

# Research Goals and Objectives

The overall goal of this methodology paper is to review and summarize the literature related to LCA within the framework of asphalt pavement construction. Additionally, on the basis of the findings of this review, this paper aims to develop an LCA framework for examining the environmental impacts of pavements in the KSA. To achieve these goals, the following set of specific objectives were identified:

- Provide an overview of standardized LCA methods and stages.
- Review and summarize previous studies on LCA techniques and their use for evaluating GHG emissions in the context of asphalt mixtures and pavements as well as the available LCA pavement tools.
- Identify the main factors and environmental input data that are needed to conduct LCA.
- Develop a general LCA approach to assess the environmental effects of asphalt pavements in KSA (Define the system boundary and data required for conducting LCA).
- Demonstrate the developed LCA framework in the context of beneficial reductions in GHGs obtained using RAP materials (example only) when producing and placing asphalt mixtures.

# LCA Overview

## Overview of Standardized LCA Methods and Stages

An LCA is a standardized approach that is used to evaluate the environmental impacts of a product, process, or service spanning its whole life cycle, from the extraction of raw materials to its disposal (Valderrama 2024). The International Organization for Standardization (ISO) took on the formal responsibility of standardizing LCA methods and procedures from 1997's ISO 14040 to 2000's ISO 14044 to ensure the consistency, reliability, and transparency of LCA studies (Mármol et al. 2023). There are currently two global LCA benchmarks:

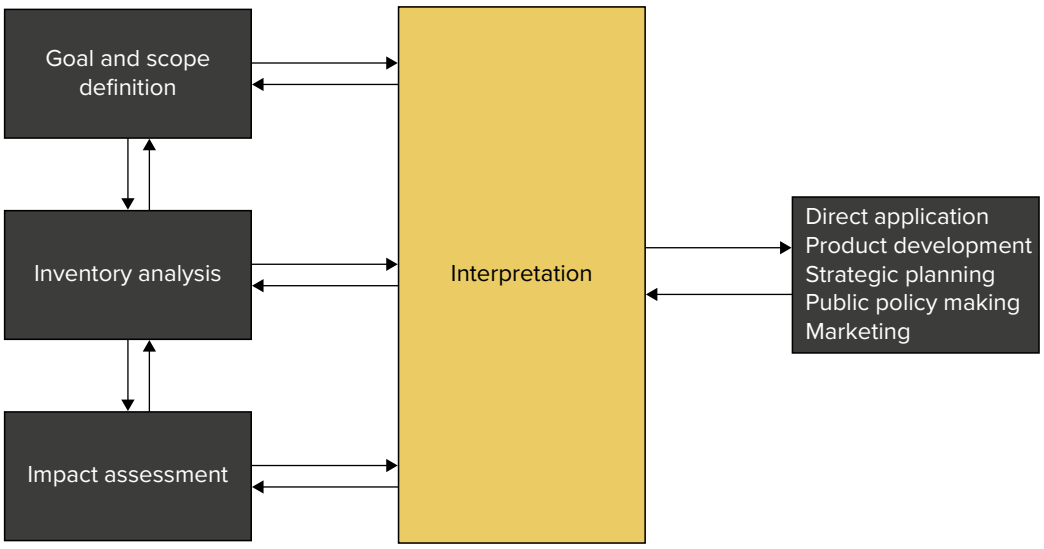
> **ISO 14040:2006**[6]: *Environmental Management: Life Cycle Assessment – Principles and Framework* (ISO 2006).

> **ISO 14044:2006**[7]: *Environmental Management: Life Cycle Assessment – Principles and Framework*. ISO standardization efforts have led to the establishment of a comprehensive methodological framework, as shown in Figure 4. Additional details on this framework are provided in the following sections of this paper.

In general, the life cycle of any product involves several stages, including 1) raw material extraction, 2) manufacturing and processing, 3) transportation, 4) usage and retail, and 5) end-of-life management and waste disposal, as shown in Figure 5.

Depending on the specific details of a particular product or system considered for analysis, the scope of the LCA can be defined on the basis of these different stages. In other words, the LCA method provides flexibility for including or excluding certain phases when calculating the environmental impact of a product. As such, three primary product LCA stages (or analysis scopes) can be implemented; these are described below (FHWA 2020; Cao 2017):

**Figure 4.** ISO Steps/phases for conducting an LCA.



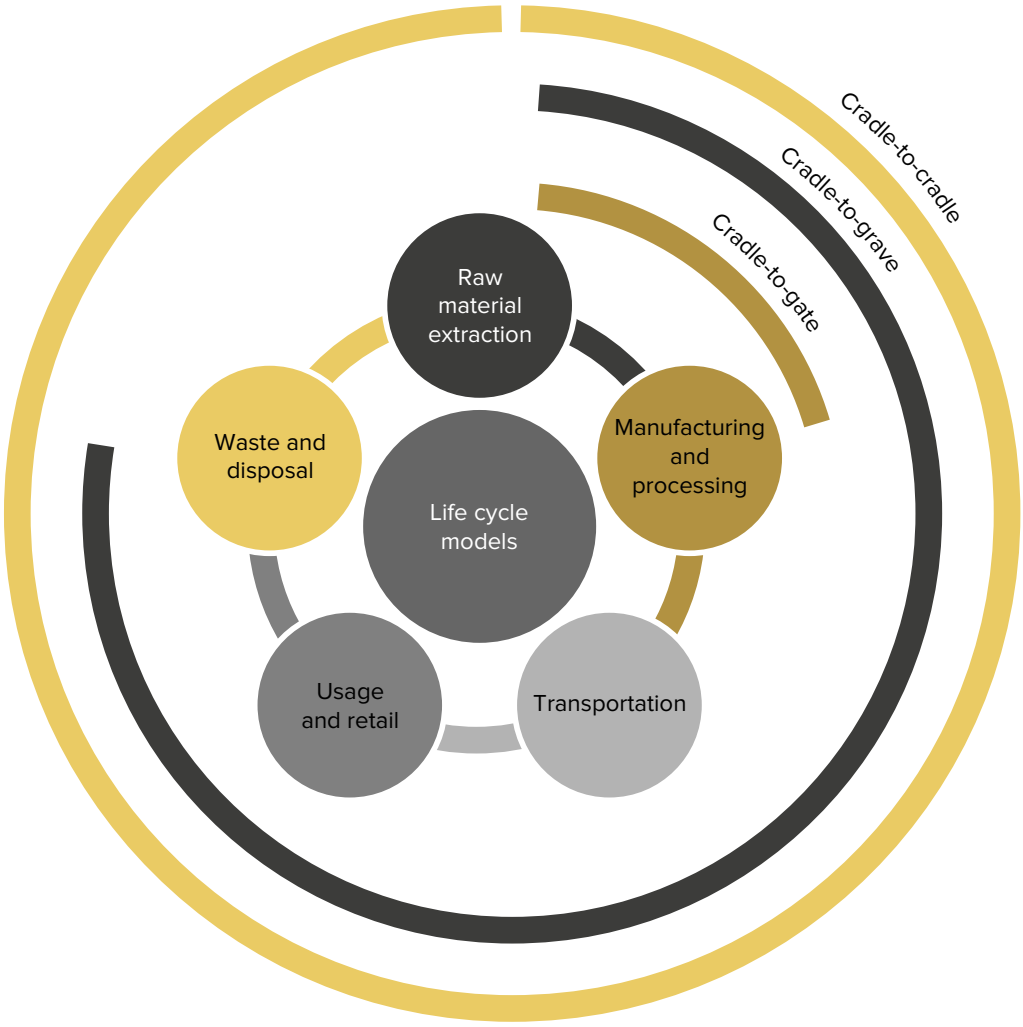

*Source:* ISO (2006).

**Cradle-to-gate** analysis focuses solely on measuring a product's environmental impact from its inception to the point of leaving its production plant, excluding subsequent transportation to the consumer. In other words, only the Raw Materials Extraction and Transportation and the Manufacturing and Processing stages are included.

**Cradle-to-grave** encompasses all five life stages of a product in the analysis. It presents an entire footprint from beginning to end with or without recycling.

**Cradle-to-cradle** is a revised edition of the cradle-to-grave approach, in which the end-of-life disposal stage is substituted with a recycling/upcycling process that enables a material to be repurposed for another product, thus fully closing the cycle.

**Figure 5.** Life cycle stages and models of a product or system.




*Source:* Ecochain (2024).

# Review of Studies on the Assessment

## Environmental Impacts of Asphalt Pavements and Mixtures

Several studies have been conducted to evaluate the effects of building asphalt pavements on the environment. These studies involved conducting LCA while considering different input and output measures along with developing computer programs (or tools) for facilitating such analyses. This section provides a detailed description, obtained through a thorough review of the literature, of the tools that are available for conducting LCAs of pavement construction and asphalt mix production, focusing on the use of RAP and warm mix asphalt (WMA). This section also discusses the various factors/measures and outputs/impacts that need to be considered when such LCAs are being conducted.

## Available Programs for Conducting LCA in Asphalt Pavements

Over the past two decades, researchers have developed various tools and methods for conducting LCAs of pavements considering the use of RAP, other recycled materials, and WMA as having the potential to reduce the negative environmental impacts of asphalt mixture production and pavement construction. Thus, stakeholders in road pavement construction can use these tools to effectively evaluate and quantify the environmental footprint linked with the construction and maintenance activities of asphalt pavements, thereby fostering more sustainable road infrastructure practices. Table 2 presents a summary of some of the LCA models available in the literature (most reported ones). Most of these tools can be tailored and revised by calibrating input and output data to align with specific needs and conditions to reflect real-world conditions in a specific context of Saudi Arabian pavement construction industry needs and conditions.

## Main Factors Considered for the LCA of Pavements

### Factors Related to Mix Production and Pavement Construction

When conducting LCAs of pavement structures, researchers usually divide the process into various stages, including raw material extraction, transportation of raw materials, production of mixtures, construction of pavement, maintenance of pavement, use and operations, maintenance and recycling, and end-of-service life. Some or all of these stages fall within the scope and goal of the selected analysis (e.g., cradle-to-gate, cradle-to-grave). In each of these stages, researchers consider several factors (e.g., Stripple (2001) developed the Life Cycle Inventory of Asphalt Pavements Model). They presented an approach for breaking down the construction, maintenance, and operation of a roadway to small unit processes, which are then used to construct a dynamic model that allows for capturing the unique differences inherent to varying roadway projects and conditions. The main factors considered in this model are energy consumption, emissions, and the consumption of raw materials.

Similarly, Hovarth (2003) defined several factors as important when conducting an LCA to assess the economic and environmental benefits of recycled materials in pavements. The first major factor is the economic benefits attained from the use of

**Table 2.** Summary of available LCA models/programs focused on pavements.

| Model | Name | Brief description | Dev. year | Source |
|---|---|---|---|---|
| PaLATE | Pavement Lifecyle Assessment Tool for Environmental and Economic Effects | LCA tool "Excel-based" for assessing environmental and economic effects of pavement construction | 2003 | Hovarth (2003) |
| AsPECT | Asphalt Pavement Embodied Carbon Tool | A tool for calculating equivalent carbon dioxide emissions for asphalt mixtures | 2009 | Nicuță (2011) |
| Open LCA | Open-Source Life Cycle and Assessment Software | A computer program for conducting LCA analysis while including major indicators from $CO_2$ to global warming potential | 2007 | Butt et al. (2014) |
| ReCiPe | N/A | An LCA tool that considers both intermediate and final environmental impacts | 2008 | Mantalovas et al. (2020) |
| CHANGER | Calculator for Harmonized Assessment and Normalization of Greenhouse-Gas Emissions | A tool that allows the estimation of road construction activities carbon footprint | 2009 | Huang, Hakim, and Zammataro (2013) |
| GHG Calculator | The US National Asphalt Pavement Association (NAPA) GHG Tool | A web-based software tool that is used for evaluating GHG emissions related to asphalt pavement manufacturing | 2009 | National Asphalt Pavement Association[8] |
| NAPA Emerald Eco | NAPA Eco Label Tool | A tool for generating Environmental Product Declarations (EPDs) | 2024 | National Asphalt Pavement Association[9] |
| PE-2 | Project Emission Estimator | A tool for estimating and monitoring greenhouse gas emissions | 2012 | Mukherjee Stawowy, and Darrell Cass (2013) |
| Roadprint | N/A | Improved version of the PaLATE program, which facilitates the use of LCAs for new and rehabilitated pavements | 2012 | Munech et al. (2014) |
| Athena Pavement LCA | N/A | A tool for calculating LCA results of asphalt and concrete pavement roadways | 2016 | Athena Sustainable Materials Institute[10] |
| LCA Pave Tool | N/A | An excel-based tool for conducting LCA of pavement structures | 2021 | Meijer et al. (2021) |

recycling materials. They reported that the rerouting of materials from landfills can lead to economic benefits. The use of recycled materials can also lead to the preservation of natural resources (reducing amounts needed for virgin aggregates), which in turn could save money for contractors and highway agencies. Additionally, Hovarth (2003) noted that recycling materials near construction sites can reduce transportation costs and fuel consumption, but the overall costs and energy savings depend on other factors related to the material being recycled.

Another important LCA factor, as defined by Hovarth (2003), is the impact of recycled materials on pavement performance. In other words, if the overall pavement produced using recycled materials performs better than or at least similar to those produced without recycled materials, then such materials would not only be economically viable but also produce long-lasting pavements. To assess these benefits, LCA can determine which material is more beneficial over the lifetime of the pavement: the use of virgin or recycled materials. Furthermore,

Hovarth (2003) noted that several environmental concerns need to be addressed when conducting LCA of recycled materials in pavements. These concerns include the need to understand the potential for harmful/toxic constituents (or metals) to leach into groundwater at concentrations higher than acceptable. In the context of RAP, Hovarth (2003) established that energy usage during the transportation of these materials is fundamental to the environmental costs and benefits. Energy consumption, fuel efficiency, truck capacity, and expected emissions are some of the major inputs that are needed for evaluating the environmental effects of employing recycled materials in asphalt mixtures, primarily because of transportation.

Huang (2007) developed an LCA model for both phases: building asphalt pavement and maintaining roads. The use of recycled materials, specifically recycled glass, tire rubber, steel slag, and plastics, is considered in this model. The main environmental factors that Huang (2007) considered in this LCA model and are relevant to the use of recycling materials include the following: 1) energy for transporting and processing recycled materials and 2) leaching of chemical toxins throughout the lifespan of a pavement structure. Energy consumption, emissions, and leaching are considered proper measures for use in Huang's model. In fact, Huang (2007) reported that energy consumption is a good indicator of key emissions ($SO_2$, $NO_x$, $CO_2$, etc.).

Nicuă (2011) evaluated the environmental impacts of using recycled materials when producing asphalt mixtures. Energy consumption and potential emissions (all expressed in equivalent $CO_2$-eq emissions) generated due to the different processes used for constructing pavements (i.e., cradle-to-gate: extraction of raw materials, logistic part for material transportation, and manufacturing mixtures) were considered important in this study.

Butt et al. (Butt 2014) presented an OpenLCA framework for quantifying environmental impacts that may associated with the processes of constructing, maintaining, and resurfacing roads. They aimed to improve the LCA conducted for asphalt pavements, specifically by considering feedstock energies, WMA additives, and polymers. Butt et al. (2014) also developed a method for calculating feedstock energy and quantifying mass and energy flows. The general LCA model proposed by Butt et al. (2014) is divided into various stages, including raw material extraction, construction material processing, construction activities, operation, maintenance, demolition, recycling, and waste treatment. However, LCA phase (e.g., cradle-to-grave analysis) was not considered in this model. Like previous models, the model developed by Butt et al. (2014) is focused on emissions produced as well as energy consumption during asphalt manufacturing and processing as the main measures for assessing environmental impacts.

Mukherjee (2016) conducted a cradle-to-gate LCA. The analysis focused on asphalt mixtures containing various recycled materials and chemical additives. Mukherjee (2016) considered three main processes when conducting the LCA analysis: material supply, mining, and production; the transportation of raw materials to asphalt plants; and plant operations to produce asphalt mixtures. The researcher also defined two types of data inputs that are necessary for conducting the analysis: primary data and secondary data. The primary data are obtained from sources that are directly observed and collected (e.g., total asphalt tons produced at a plant, total electricity, hot-oil heater energy, generator energy, aggregate tons used in production, mobile equipment energy, asphalt binder tons used in production, one-way distance traveled to plan (raw materials), water tons used, and stack emissions from plants). The secondary data are

defined as those obtained from sources other than primary sources or those that have not been directly observed. Examples of these data include details of petroleum refining obtained from the National Renewable Energy Laboratory (NREL) in the United States.

Vega et al. (2019) conducted an LCA to evaluate the impact of WMA produced from three different recycled concrete aggregate (RCA) materials (RCA used as partial replacement for natural aggregates). Like in previous studies, Vega et al. (2019) considered energy consumption and transport distance when producing WMA and HMA. Only the cradle-to-gate scope was considered in this LCA. On the basis of the LCA results, the researchers reported that the use of RCA results in an increase in the optimal asphalt content in these mixtures, potentially leading to greater negative environmental impacts than those stemming from traditional mixtures.

Cao et al. (2019) investigated the environmental impacts of using LCA for WMA containing asphalt rubber. They also conducted a sensitivity analysis of energy consumption in the different processes needed to produce WMA with asphalt rubber. The LCA stages considered by Cao et al. (2019) included the material extraction and production, transportation, construction, and use stages. The LCA results indicate that the use stage had the greatest impact on the energy consumption of WMA pavements, thus indicating the importance of understanding the system boundaries when conducting an LCA of pavements. Additionally, Cao et al. (2019) reported that using Asphalt Rubber in WMA led to “greater probabilities” of reducing energy consumption.

Ma et al. (2019) compared the environmental impacts of WMA with those of HMA. With an approach similar to that of other studies, the researcher evaluated resource consumption when conducting their LCA. On the basis of the LCA results, Ma et al. (2019) reported that the resource consumption of WMA and HMA throughout their service lives was similar; however, the GHG emissions and particulate matter emissions were significantly lower for WMA than those measured for HMA.

More recently, Hasan et al. (2020) conducted an LCA to calculate the environmental impacts of asphalt mixtures containing WMA technology, recycled materials, and other materials in a case study in Abu Dhabi. They considered air emissions and energy consumption for earthwork, pavement placement, concrete barriers, etc. A cradle-to-grave assessment was conducted as part of this study. Hasan et al. (2020) reported that earthworks accounted for a significant portion (26% of emissions) of complete roadway construction. On the basis of a comparison of WMA and HMA, the LCA results showed that WMA led to significant reductions in emissions.

Overall, the studies above highlight a main theme or set of factors that should be considered in LCAs of pavement systems. These main factors are summarized as follows:

> Emissions for pavements are typically quantified via the energy consumed during material production as well as the transport of these materials (whether they are raw materials or actual asphalt mixtures). The energy consumption of the different activities involved in the creation of asphalt mixtures or the construction of pavements should be quantified.

> The scope of the LCA analysis is an important factor that needs to be considered. Most of the

abovementioned studies highlight a cradle-to-gate type of analysis for asphalt mixtures. If the pavement lifecycle is required in the analysis, it is then best to conduct a cradle-to-grave assessment.

Other potential economic and performance benefits should also be considered in addition to conducting LCA analysis. These benefits or factors depend on the green technology being considered for LCA. Moreover, new technologies and materials that can potentially help reduce the environmental impacts of asphalt pavements should also consider their performance to be at least equal to that of traditional technologies, if not better.

## Environmental Impact Categories that Are Commonly Reported for Asphalt Pavements

In addition to the abovementioned studies, highlighting the importance of measuring the energy consumption of various processes or stages of producing asphalt mixtures, researchers have also considered several environmental impact categories that are essential when conducting LCA. These factors include climate change, photochemical ozone formation, stratospheric ozone depletion, acidification, particulate matter formation, and eutrophication. A concise overview of each impact category is outlined below:

**Climate Change**[11] is characterized through the global warming potential (GWP, measured in units of kg $CO_2$-eq). This approach facilitates comparisons of the climate change impacts of various gases. Specifically, the amount of energy that is absorbed by a certain gas relative to that absorbed by $CO_2$ is measured.

**Stratospheric Ozone Depletion**: This is measured in terms of ozone depletion potential (ODP, in units of kg CFC-11-eq). ODP measures the damage that certain GHGs can cause to the ozone layer compared with that caused by trichlorofluoromethane (CFC-11).

**Photochemical Ozone Formation**: This is characterized by the photochemical formation potential (POPC, in units of kg $No_x$-eq). POPC is used to assess the capacity of volatile organic compounds to generate ground-level ozone.

**Acidification**: This is measured via the acidification potential (TAP, expressed in kg SO2-eq). This measure refers to compounds that may lead to acid rain.

**Eutrophication**: This is measured via freshwater eutrophication potential (FEP, in units of kg PO4-eq). This refers to the potential increase in plant growth attributable to the accumulation of nutrients in water and soil.

**Particulate Matter Formation**: This is characterized by the particulate matter formation potential (PMFP), which is expressed in kg PM2.5-eq. This refers to particulate matter that is finer than 2.5 microns in diameter and can be derived from different emission sources.

To assess these impacts on the environment, researchers have utilized several life cycle impact assessment (LCIA) methods. Two of the most common methods utilized in pavement applications are the TRACI (Tool for the Reduction and Assessment of Chemical and Other Environment Impacts) model, developed by the U.S. Environmental Protection Agency (EPA), and the ReCiPe model (Ivel et al., 2020; Mukherjee 2016). A brief description of both models is provided as follows:

**TRACI**: An environmental impact assessment tool that was developed by the US EPA. It offers the characterization factors of conducting an LCIA that can be used in LCA. It revolves around several effect groups in common equivalent units, including climate change, ozone depletion, smog formation, acidification, eutrophication, human health impacts, and ecotoxicity.[12]

**ReCiPe**: This is an LCIA method that was first developed in 2008 by Radboud University Nijmegen, Leiden University, and PRe-Sustainability. Like TRACI, this method helps convert life cycle emission inventories into environmental indicators.[13]

# Research on Technologies to Minimize the Environmental Effects of Asphalt Mixtures

Several techniques can be used to reduce the environmental impact of asphalt mixtures. These techniques include but are not limited to 1) recycling RAP into new asphalt mixtures, 2) the use of WMA technologies, 3) the use of electric or more efficient fuels at plants (e.g., the use of natural gas instead of diesel for heating aggregates), and 4) the air drying of aggregates. This section presents a review of various studies showing the benefits of using RAP and WMA in asphalt mixtures for reducing GHG emissions.

## RAP and its Environmental Effects on Asphalt Mixtures

Various studies have been conducted to assess the environmental impacts of using recycled materials in asphalt mixtures. For example, Lee et al. (2010) conducted an LCA and a Life Cycle Cost Analysis (LCCA) on conventional pavement structures and those containing recycled materials in Wisconsin, USA. Overall, Lee et al. (2010) reported that incorporating recycled materials in base and subbase layers resulted in a 20% reduction in GWP, a 16% decrease in energy consumption, an 11% reduction in water consumption, and an 11% decrease in hazardous waste generation. All these benefits were reported, while the use of recycled materials led to 21% cost savings in comparison with conventional pavements. Similarly, Nicuă (2011) used the asPECT program and suggested that adopting recycled materials to produce asphalt mixtures leads to an approximately 40% reduction in $CO_2$-eq emissions in comparison to traditional asphalt mixtures. Butt et al. (2014) reported that the transportation of materials is a key factor in energy consumption and emissions. Mukherjee (2016) compared LCA results for producing a traditional mix and a mix containing 15% RAP and reported significant reductions in the negative environmental impacts of asphalt mixtures (e.g., the GWP decreased from 58.6 to 35.9 kg of $CO_2$-eq/ton).

Mantalovas et al. (2020) performed a cradle-to-grave LCA to assess the environmental benefits of using RAP and biobased binders in the production of asphalt binders and pavements. Specifically, three pavement alternatives – one baseline conventional pavement and two biobased pavements (one with recycled asphalt and another without) – were considered in this analysis. The researchers utilized the ReCiPe 2016 to conduct the analysis, as it allows the use of midpoint and endpoint impact category indicators. On the basis of these analyses, Mantalovas et al. (2020) reported that biobased pavements reduce GWP. They also reported that the cradle-to-gate stage of the assessment is the most significant in terms of environmental impacts. In other words, this stage should be considered when implementing measures to mitigate possible environmental impacts. Thus,

raw material production should be the main focus. The use of RAP materials has also been reported to reduce the negative environmental impacts of asphalt pavements.

Abdalla, Faheem, and Walters (2022) conducted a comparative cradle-to-gate LCA to assess the environmental benefits of utilizing recycled materials (RAP, fly ash, and food waste bio-oil) in asphalt mixtures and pavements. Different percentages of RAP in mixtures were considered in the analysis (i.e., 0% to 100% RAP). OpenLCA software was used to conduct all the analyses considered. On the basis of these findings, Abdalla, Faheem, and Walters (2022) reported that the use of RAP resulted in reduced environmental impacts on asphalt mixtures (by up to 80% reduction in GWP if a 100% RAP mixture was used). The researchers also reported that the use of higher RAP percentages led to greater reductions in environmental impacts than did the use of conventional mixtures.

Overall, the use of RAP in asphalt mixtures, as shown in previous studies, helps reduce the environmental impacts of asphalt mixtures. This is especially the case with the increase in the RAP percentage within an asphalt mixture.

## Environmental Benefits of WMA Technologies on Asphalt Mixes

WMA is another prominent technology that can be used to reduce the negative environmental impacts of asphalt mixtures. These technologies facilitate the manufacturing of asphalt mixtures at temperatures lower than traditional levels, which leads to various environmental benefits, such as reducing the amount of fuel consumed during the heating of aggregates.

To evaluate the environmental effects of WMA and RAP on asphalt mixtures, Vidal et al. (2013) conducted an LCA on WMA and HMA. The researchers conducted a cradle-to-grave LCA and reported that the use of reduced temperatures during the production of WMA reduced the environmental impacts of those mixtures; however, this reduction was offset by the greater impacts of the materials used (i.e., synthetic zeolite WMA technology). Additionally, they noted that the use of RAP with WMA facilitates the reduction of environmental impacts by 13% to 14% through the addition of 15% RAP into the mixtures. Vidal et al. (2013) reported that WMA is still beneficial, as such technology can allow the use of more RAP in asphalt mixtures.

Rodriguez-Alloza et al. (2015) conducted an input–output LCA of WMA. The researchers conducted the LCA on a total of 39 asphalt mixtures with and without a rubber binder and used Fischer-Tropsch (F-T) wax as the WMA technology for reducing binder viscosity. On the basis of the LCA findings, Rodriguez-Alloza et al. (2015) reported that the wax WMA technology used significantly saved energy and reduced GHG emissions by 18% to 20% compared with their HMA counterparts. They also reported that an average reduction in plant mixing temperature of 8°C is necessary to attain those benefits because of the use of F-T wax in the production of WMA (which offsets some of the environmental benefits attained by reducing production temperatures).

Hassan (2010) conducted cradle-to-gate LCA to examine the environmental and economic benefits of WMA. Several WMA technologies, including Aspha-Min, WAM-Foam, Sasobit Wax, and Evotherm chemical, have been considered. On the basis of the LCA findings, Hassan (2010)

reported that the use of WMA reduces air pollution by 24%, fossil fuel consumption by 18%, and smog formation by 10% compared with traditional HMA mixtures. Overall, Hassan (2010) reported that WMA is estimated to reduce the environmental impacts of asphalt mixtures by 15%. Specifically, Hassan (2010) reported that WMA leads to a reduction in fossil fuel consumption by 18% and in air pollution by 24% compared with HMA.

Milad et al. (2022) utilized an LCA to compare the environmental impacts of WMA and HMA. They reported that the usage of WMA contributes to significant reductions in energy consumption, thus leading to a reduction in the negative environmental impacts of asphalt pavements (or, in other words, a reduction in emissions).

In general, the studies reviewed above show that the use of WMA has the potential to reduce the negative environmental impacts of asphalt mixtures. However, this depends on the scope of the LCA analysis conducted by various studies and the consideration of the impacts of WMA additives or technologies over the overall life cycle of WMA mixtures.

# General LCA Framework for Evaluating Asphalt Pavement Emission in Saudi Arabia

The general LCA framework in this paper, the Saudi Arabian Pavements Life Cycle Assessment (SAPLCA), consists of four major phases following the ISO 14040 guidelines. These phases include the definitions of goal and scope, life cycle inventory analysis, life cycle impact assessment, and results interpretation. The following subsections describe the LCA model specifically proposed for evaluating the environmental impacts of Saudi Arabian asphalt pavement infrastructure.

## SAPLCA Goal and Scope

In this stage, the boundary, level of detail and timeframe for the LCA analysis are defined. For the SAPLCA, the proposed LCA analysis level is a cradle-to-gate level. This type of analysis is proposed because it is the most relevant to the environmental impacts of pavements, as reported by Mantalovas et al. (2020). Several other researchers have utilized this LCA analysis level for their studies (Moretti 2017; Anthonissen, Van den Bergh, and Braet 2014; De Pascale et al. 2023). The analysis conducted in this study is particularly well suited for comparing the environmental ramifications of asphalt mixtures incorporating significant levels of RAP and WMA additives. This suitability arises from the fact that the environmental effects of WMA compared with those of traditional HMA with high RAP contents are anticipated to be comparable, given their similar construction methodologies. Thus, the primary distinction between these mixtures stems from processes occurring prior to and during their production in asphalt plants. Additionally, the complexity of predicting the long-term use stage and the end-of-life stage for pavements make it difficult to collect data to include such stages in the analysis.

Given this definition, the SAPLCA involves three main stages related to pavement construction: **raw material production, transportation of raw materials, and, finally, production of asphalt mixtures**. Notably, the SAPLCA focuses only on hot asphalt mixtures, as they are the most commonly used mixes for paving roadways in Saudi Arabia, as well as WMA, which is a potential method that might be used as an alternative to hot mixture asphalt to decrease the energy need and the environmental impact. No cold mixtures are considered as part of this model.

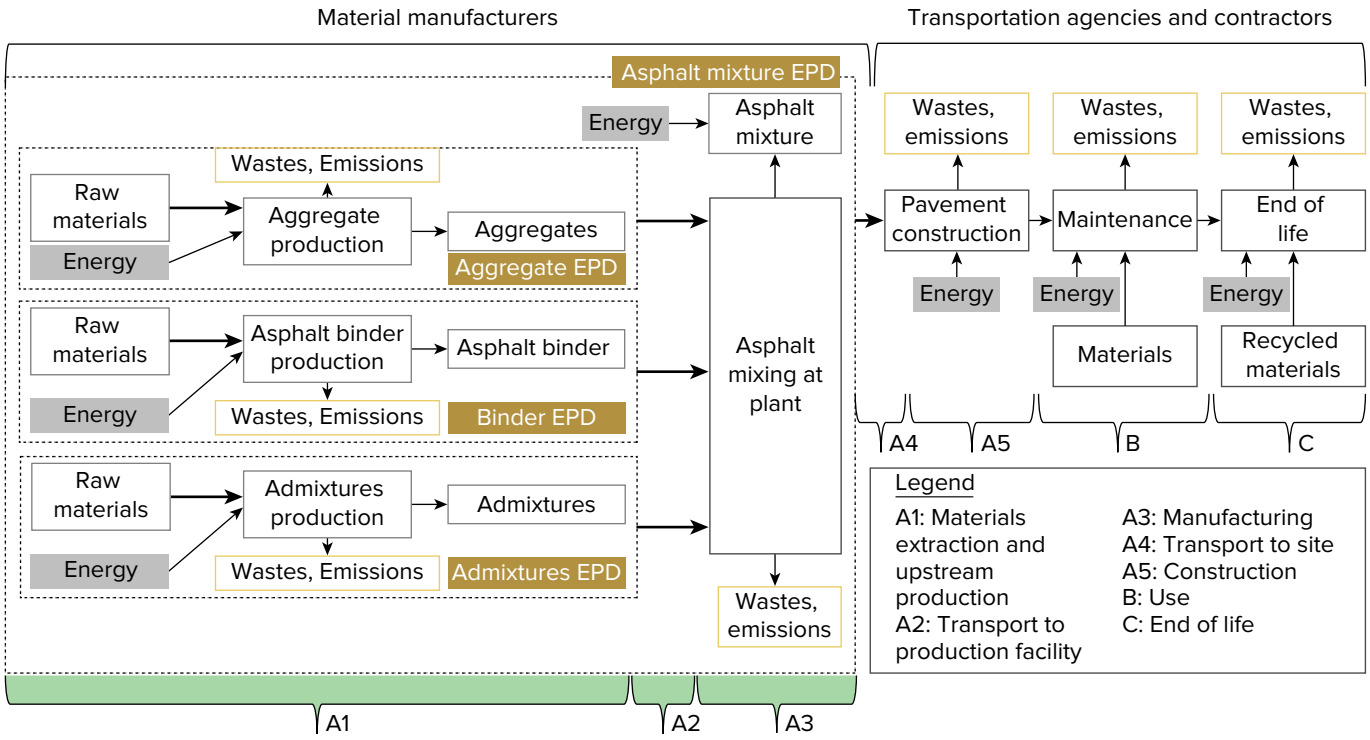
## SAPLCA Inventory Analysis

The inventory analysis revolves around collecting data for inputs and outputs within the different stages of the LCA scope (or boundaries) selected in the previous stage. Since the SAPLCA is a cradle-to-gate model (Figure 6, A1 to A3 processes highlighted in Green), the following processes are considered in the assessment:

### Production of Raw Materials

- **Natural Aggregates**: To produce aggregates for asphalt mixtures, rock quarries are usually blasted with explosives and then conveyed into crushers to produce the proper gradations (i.e., size distribution leading to later production of dense graded or other types of HMA mixtures). Sand and gravel are usually excavated from natural sources (e.g., rivers; in the case of Saudi Arabia, wadis are dry riverbeds) or quarries, where they are mined from rock formations such as limestone, granite, and sandstone. The data

**Figure 6.** System boundaries (cradle-to-gate) for SAPLCA.




Source: FHWA (2020a).

needed to produce natural aggregates are "energy" consumed by the equipment used during the production process. This process is referred to as "Energy in Natural Aggregates Production."

- **Asphalt Binder**: The process of producing asphalt binders involves extracting crude oil, transporting it into a refinery, refining the oil, and ultimately producing an asphalt binder. During this process, petroleum refineries typically use electricity and other sources (oil such as diesel or natural gas) of energy for heating and transportation purposes. The data required for this category are "Energy Consumption to Produce Asphalt Binders."

**Production of RAP**: The process of producing RAP involves first milling an existing, deteriorated asphalt pavement layer from a roadway being rehabilitated. Once the millings are obtained, they are usually taken into a plant for crushing, fractionating (i.e., separating the RAP into different sizes), and stockpiling. The energy used for all equipment needed for milling, transporting, fractionating, and stockpiling RAP is the necessary data input for this process. This is referred to as "RAP Production Energy Consumption."

- **Additives for WMA**: Several WMA technologies or additives that exist in the

current market facilitate the production of asphalt mixtures at temperatures lower than traditional levels; hence, the name Warm. Some of these technologies include Aspha-min, Sasobit, and Evotherm, among others. Depending on the additive used when preparing WMA mixtures, the energy consumed to produce this additive is a necessary input into the LCA analysis.

**Transportation of Raw Materials to Asphalt Plants**: In this process, raw materials are usually transported from their stream sources to an asphalt plant to produce asphalt mixtures. Usually, loaders and dump trucks are used for this purpose. Thus, the energy used during this process to operate such equipment is a major input in the analysis. Additionally, the travel distances between an asphalt plant and aggregate quarries (or refineries) are necessary to ensure accurate calculations of environmental impacts. Notably, RAP materials are usually stockpiled at asphalt plants; thus, their transportation is not significant. If they are not readily available to the plant producing the HMA or WMA, then the transportation of RAP materials must be considered in the analysis. Other modes of transportation, such as rail, are also considered in this model.

**Production of HMA or WMA**: This process involves first heating both aggregates and asphalt binders. The aggregates are heated to ensure that they are fully dry before being mixed with the binder. Asphalt binders are also heated to ensure that they are flowable (to reduce their viscosity). Both materials are also heated to ensure proper coating. Once both materials are heated, they are mixed at the proper proportions. A typical HMA mixture contains 95% aggregates and 5% binder by total mix weight. This process is usually completed in a drum or a batch plant that typically uses both electricity and alternative energy sources such as natural gas for heating and mixing operations. Thus, the energy consumed during the manufacturing process of asphalt mixtures is the main data input for the SAPLCA.

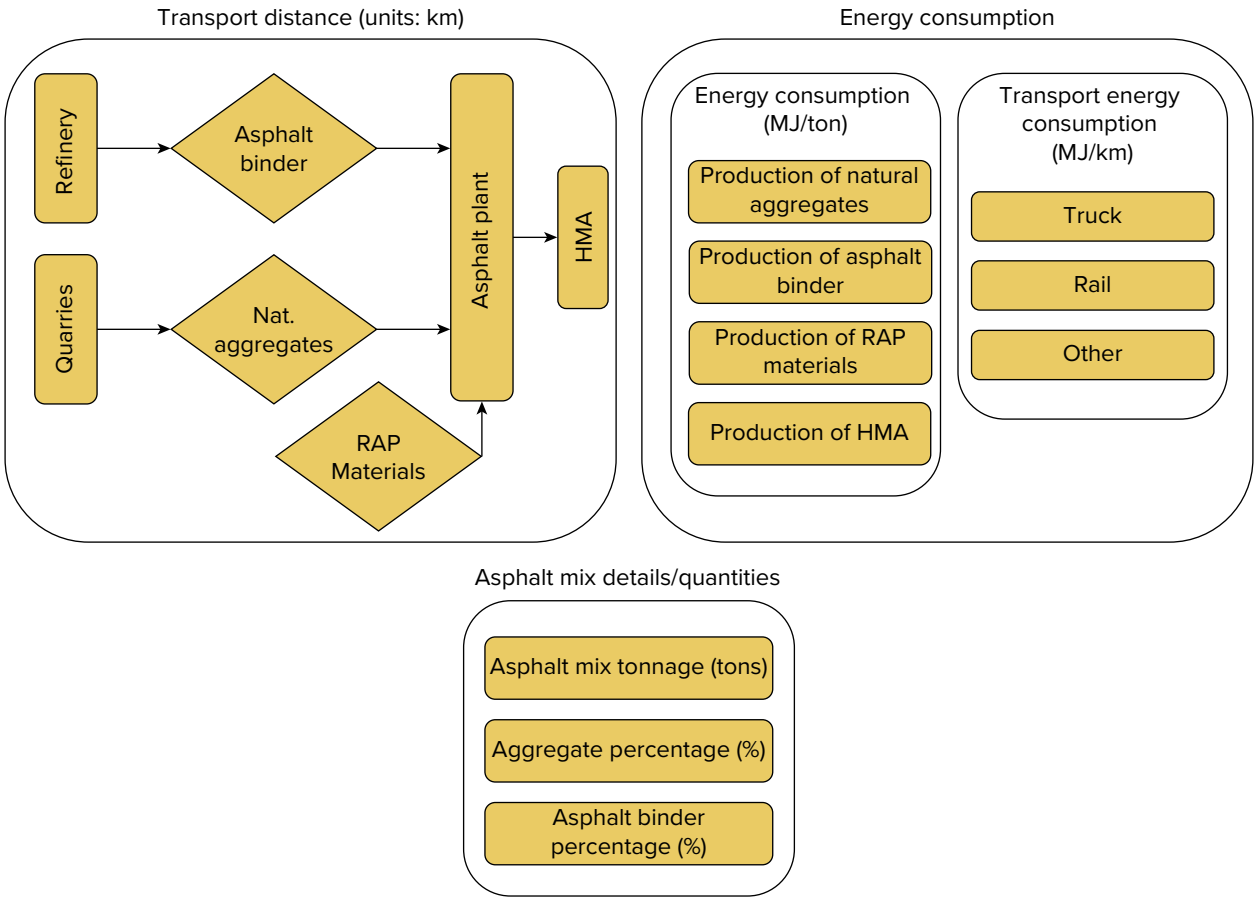
Figure 7 presents the parameters (inputs) for all the processes defined above for the SAPLCA model.

Once all the energy data for all the process parameters are collected, as discussed, the next step in the SAPLCA is to calculate a life cycle inventory (LCI) for the activities involved in an asphalt mixture project. Typically, emissions from a process are generated from two sources: one is the process itself (i.e., the use of diesel fuel combustion to crush aggregates), and the other comes from the activity of producing the energy required for that activity. The following provides an explanation of the necessary loadings (or "conversion" factors) for each of the SAPLCA LCI processes:

**Energy Production**: This refers to the energy consumed to generate electric power. Typically, a distribution loss of 5% is assumed (EURPROG 1998). Similarly, energy production refers to the energy needed to produce diesel fuel (or other types of fuel) before combustion. The emissions associated with generating energy (electricity, diesel fuel or renewable energy) can be obtained from the literature (e.g., Stripple 2001; Huang, 2007). Emissions are usually expressed as grams per MJ of energy produced.

**Combustion of Fuel**: This refers to the energy needed during the operation of equipment needed to complete a process. Emissions and pollutants from the combustion of fuel are also represented as grams per MJ of energy consumed.

**Figure 7.** Process parameters for raw material production, transport of materials, and production of HMA and WMA.




*Source:* Authors.

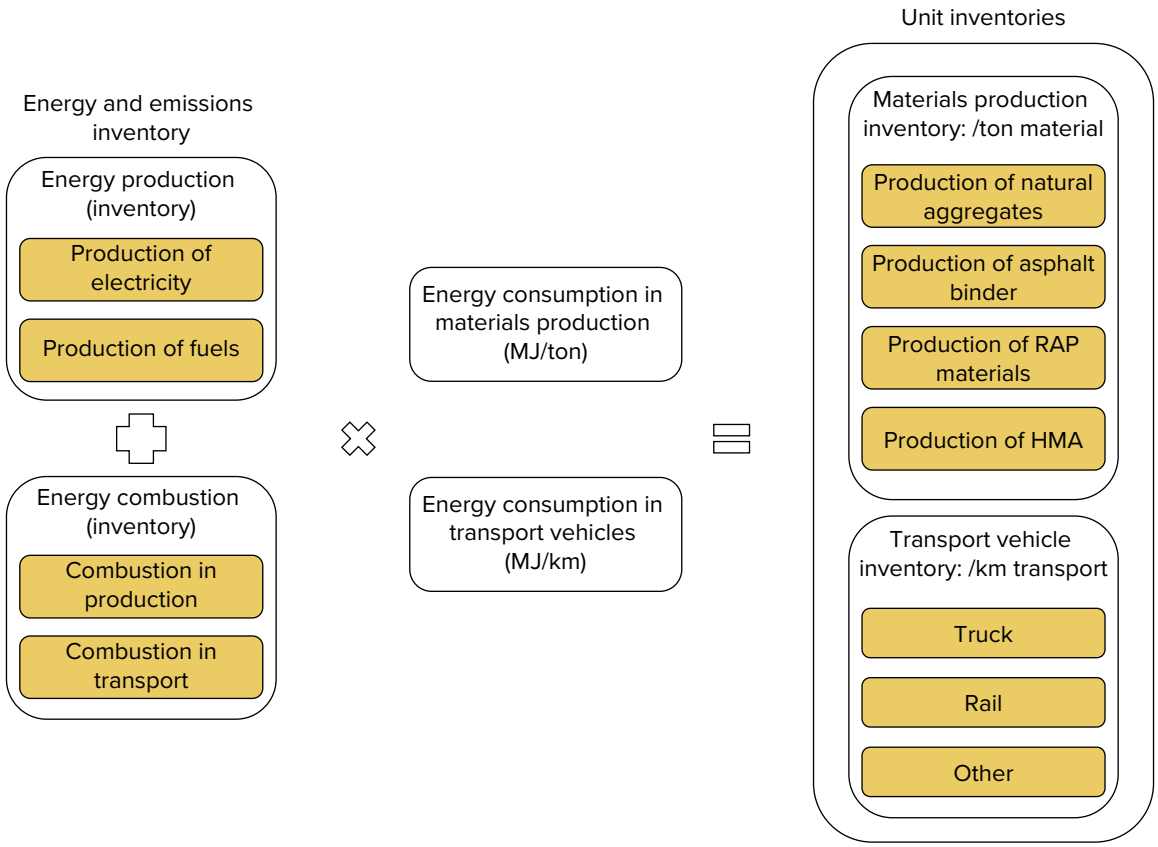
**Transport Vehicle Operation**: This refers to the use of trucks and other modes of transportation, such as rail, for moving materials from one stage to another (e.g., moving raw materials from quarries to asphalt plants). Since different types of trucks and transport vehicles are available, an inventory of the equipment is necessary along with the emissions generated from each. The transport distance is also a factor in the calculation. To obtain the LCI loading for transport vehicles, one can calculate transport vehicle emissions by multiplying the vehicle's fuel consumption (MJ/km) by the total emissions from both energy production and energy consumption (the two items above for the vehicle).

**Asphalt Mix Production**: Similar to transport vehicle operation, the energy consumed to produce energy and combust to operate equipment is considered. Emissions from these processes are usually expressed in g/MJ and are calculated in a similar fashion to those of the transport vehicles.

Figure 8 presents the general equation for calculating the energy and emissions inventory for the SAPLCA.

After the process of calculating unit inventories for the different processes is completed, the next step in the SAPLCA is to calculate the project level

**Figure 8. General equation for calculating unit inventories for use in the SAPLCA.**




*Source:* Authors.

inventories (PLIs) for a particular project. Since this paper focuses on only the production of asphalt mixtures, information about mix production tonnage and transport data is used. The calculations of the PLIs are straightforward; multiply unit inventories by the tonnage and transport distances.

Table 3 presents a summary of the key processes considered for the SAPLCA along with the data sources and additional remarks on those sources.

## SAPLCA Impact Assessment

In this stage, a characterization model (or models) is selected for each impact category. Usually, the inputs and emission outputs from PLIs alone are not sufficient to provide an understanding of how such emissions are harmful to humans or the environment. Thus, the impact of each of these emissions on the environment and humans needs to be established. For the SAPLCA, the impact categories identified in the previous section (i.e., climate change, photochemical ozone formation, stratospheric ozone depletion, acidification, particulate matter formation, and eutrophication) are considered in the analysis. The impact of one or more pollutants on these categories is then examined. Figure 9 shows the assignment of pollutants to different impact categories as adopted from Huang (2007). For each impact category, the

**Table 3.** SAPLCA key processes and potential data sources identified.

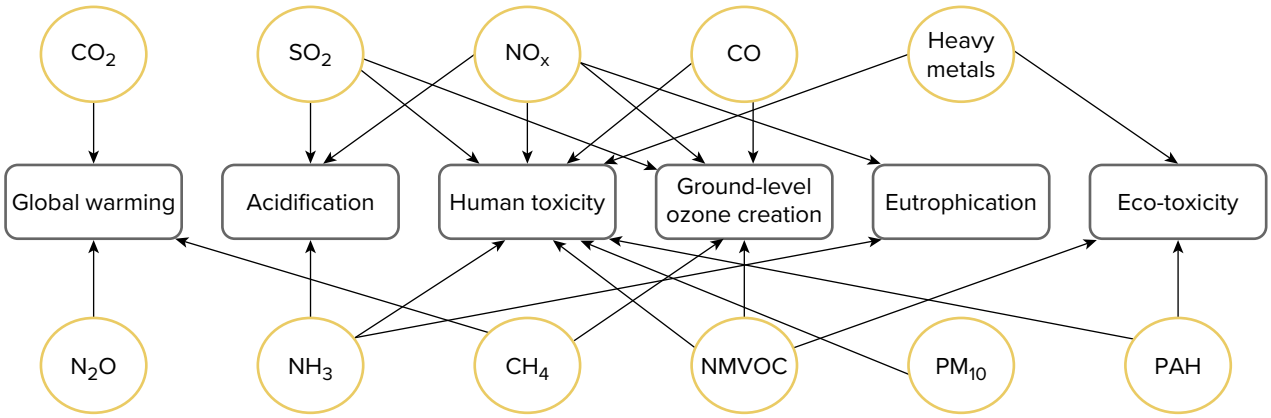
| Stage and processes | Data source | Additional comments |
|---|---|---|
| A1. Raw Materials Production, including:<br>• Crude oil extraction, refining, and storage; Extraction, production, and transport of diesel and other fuels; Production and transmissions of electricity to plants; and Production and transport of raw materials (aggregates, binders, and RAP) to asphalt plants. | Production of aggregate and transmission of electricity data for KSA is available in Ecoinvent database. Asphalt binder data available in the United States federal LCA commons database[14] | Open access set of data specific to processes related to asphalt mixtures and other processes involved in LCA. These data are readily available for the OpenLCA software |
| A2. Raw Materials Transport to Production Facility, including:<br>• Crude oil transport from well to refinery; Transportation of liquid binder to asphalt plant; and Transportation of virgin and RAP materials from crushers to plants. | Ecoinvent database of KSA and Survey of Asphalt Plants in the KSA | Transport distances and tonnage will be estimated for moving materials from sources to plants using a survey to be prepared and distributed to asphalt plants |
| A3. Production of Asphalt Mixtures, including:<br>• Energy used during the production of asphalt mixtures; including fuel and electricity consumption and other plant operations; and plant outputs characterized through available data on total stack emissions generated per ton of asphalt mix produced. | Survey of asphalt plants in the KSA supplemented by data from literature and the Ecoinvent database | The energy consumption and stack emissions at plants in the KSA will be collected through a survey distributed to select asphalt plants in the country. This survey will be distributed with the assistance of the KSA's Ministry of transport |

pollutants have a certain weight (or factor) that can be used to calculate the overall impact. This is done by multiplying the weightage with a pollutant's emissions (in grams) and summing the results for all pollutants contributing to the category in hand. Since the US EPA's TRACI tool includes the impact categories considered in the SAPLCA, this tool will be used for conducting the LCIA. Appendix B presents additional details about the TRACI tool.

## Interpretation of the SAPLCA Results

In the results interpretation stage, all findings are compiled and evaluated to inform conclusions and recommendations. Then, any questions related to the environmental impact of transport distance, the percentage of RAP in the mix, and the use of different, more efficient heating sources can be answered.

**Figure 9.** Pollutants/emissions and their contributions to LCA impact categories.




*Source:* Huang (2007).

# Demonstration of LCA for Asphalt Mixes with Varying Percentages of RAP Content

This section presents an example to assess the impact of using RAP materials at different percentages (0% or no RAP, 20%, and 35% high RAP) on the environment. At this stage, data obtained for asphalt mixtures and plants in the United States were used, and the analysis was conducted via the U.S. Federal Highway Administration's (FHWA 2020) LCA Pave tool for simplicity. The primary objective of this example is to highlight the importance of understanding GHG emissions from asphalt mixtures and using high RAP as a strategy to mitigate these emissions. Notably, LCA Pave is an advanced tool for analyzing the environmental impacts of pavement alternatives. This program uses the TRACI LCIA tool as part of the analysis. This analysis for Saudi Arabia will be conducted at a later stage of this study while other emission reduction strategies are also being studied. The following subsections provide details about the inputs used for the analysis, the factors considered (based on LCA Pave), and the LCA findings.

## Case Study Input Parameters

To assess the environmental impact of varying RAP content percentages, three HMA mixtures are considered. These mixes include the following:

Alternative No. 1 (Business as Usual -No RAP) Mix Constituents:

- Coarse Aggregates Proportion: 48%
- Fine Aggregates Proportion: 47%
- Asphalt Binder Content: 5%
- RAP Content: 0%

Alternative No. 2 (20% RAP) Mix Constituents:

- Coarse Aggregates Proportion: 37.9%
- Fine Aggregates Proportion: 37.1%
- Asphalt Binder Content: 4% (1% reduction in virgin binder due to RAP binder)
- RAP Content: 20%

Alternative No. 3 (35% High RAP) Mix Constituents:

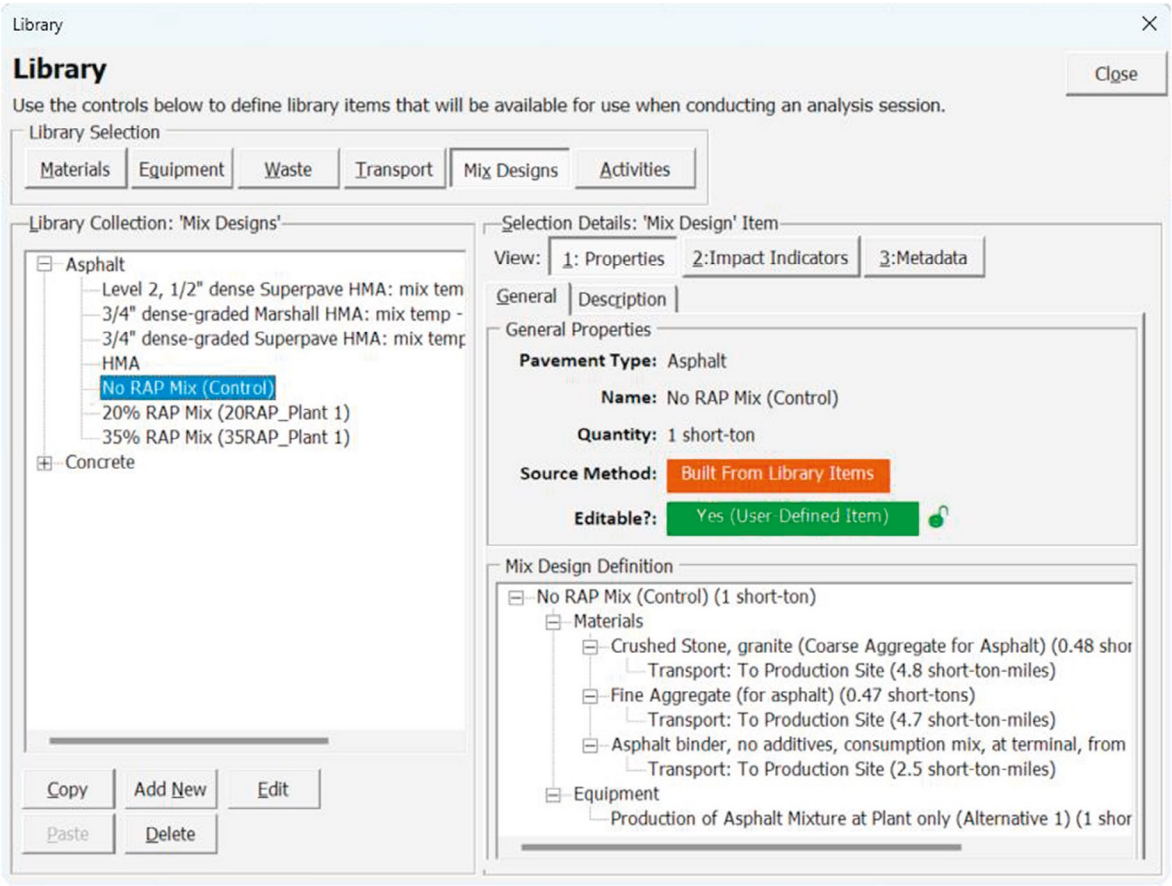
- Coarse Aggregates Proportion: 30.3%
- Fine Aggregates Proportion: 29.7%
- Asphalt Binder Content: 3.5% (1.5% reduction in virgin binder due to RAP binder)
- RAP Content: 35%

All mixes were defined in the LCA Pave program, as shown in Figure 10.

In addition to mix constituents, other input information related to the transport distance of raw materials, mode of transport for raw materials, total quantity of mixture production, and lane length and width was necessary. Since all these mixtures are similar (i.e., produced at the same plant via the same binders, virgin aggregates, or RAP), with the only variables being the RAP and virgin asphalt binder contents, all other input parameters were kept constant for all the mixtures (e.g., the transport distance was kept constant for all the virgin aggregates). Table 4 shows the values used for all these inputs.

Furthermore, the impact analysis factors considered in the analysis were limited to those employed by

**Figure 10.** Addition of all alternative mixtures into the LCA Pave data library.




*Source:* Authors' analysis via the LCA Pave tool.

the LCA Pave program. These mostly matched those defined for the SAPLCA model above. These impact factors include acidification, eutrophication, GWP, smog formation, fossil fuel depletion, and ozone depletion. The energy requirements for all the different processes are also well defined for typical asphalt plants and material production processes in the LCA Pave program. These values were used in the calculations.

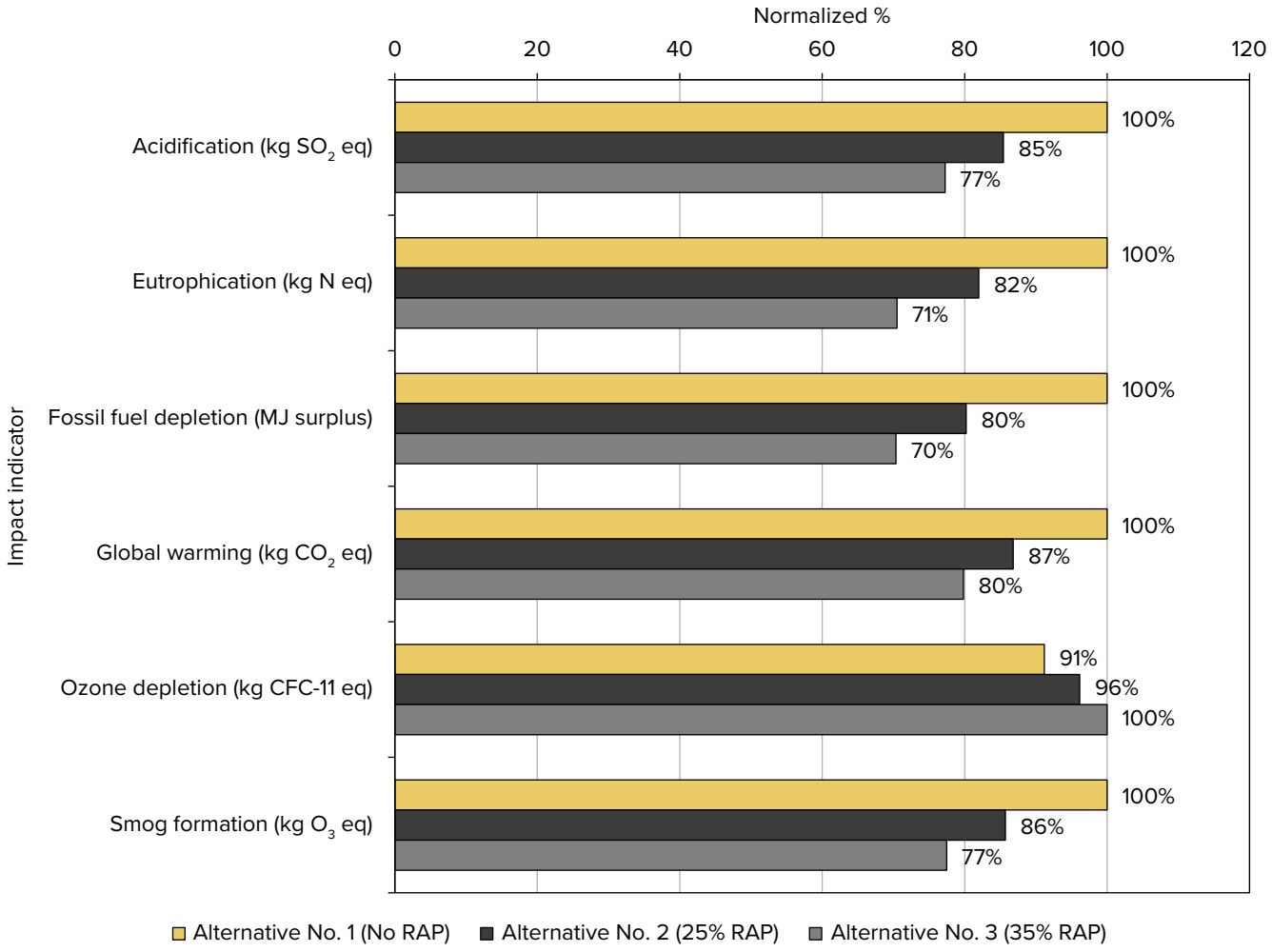
## Analysis of Results

Figure 11 presents the normalized percentage (normalized in reference to business-as-usual alternative no. 1) for all impact categories (except for ozone depletion, which is normalized for alternative no. 3). The figure clearly shows that the increase in the RAP content in the asphalt mixtures led to significant reductions in the environmental impact. For example, Alternative No. 3 had a lower (by 20%) GWP than the control mixture without RAP materials. Given these benefits, the use of more RAP materials in their mixtures is recommended, as this would lead to reductions in GHG emissions and their harmful impacts. The maximum percentage of RAP in the mixture, however, should be limited to a value that does not compromise the mechanical performance of asphalt mixtures.

**Table 4.** Summary of available LCA models/programs focused on pavements.

| Parameter | Value |
|---|---|
| Transport distance, coarse and fine agg. (miles) | 50, 1 mile for RAP |
| Mode of transport, coarse and fine agg. | Road, using a combination truck (avg. fuel) |
| Asphalt binder transport distance (mile) and mode | 10 miles; mode is rail |
| Equipment for mix production | Asphalt mix plant (alternative 1 in LCA pave) |
| Construction lane width (ft) and length (miles) | Width: 12<br>Length: 1 |

**Figure 11.** Comparison of normalized impact indicator values for the different asphalt mix alternatives.




*Source: Authors' analysis via the LCA Pave tool.*

# Summary, Conclusions, Recommendations, and Policy Implications

Given the urgency of the climate emergency and Saudi Arabia's commitment to achieving net-zero GHG emissions, the decarbonization of transportation infrastructure, including the construction and maintenance of road pavement, must be accelerated.

In line with the Kingdom's environmental aspirations, this paper was prepared with the goal of reviewing and summarizing the literature pertaining to LCA in the setting of asphalt pavement construction to establish an LCA methodology for asphalt mixtures in the KSA. On the basis of the findings of this review, an LCA framework for examining the environmental impacts of pavements in the KSA is proposed. The recommended framework was based on the most up-to-date ISO 14044 guidelines for LCA and findings from the literature focusing on the main factors influencing GHG emissions from asphalt mixtures and pavements. A demonstration of the approach, albeit not yet customized to Saudi Arabia's conditions, was also conducted to showcase how LCA can be used to investigate different strategies (in this paper, the use of high RAP) for reducing emissions from asphalt mixtures.

On the basis of the findings from the literature review and demonstration of LCA for high RAP content, the following conclusions were drawn:

- LCA is the predominant approach for evaluating the environmental impacts of asphalt pavements.
- A comprehensive LCA framework named SAPLCA was defined for assessing the environmental impacts of asphalt pavements in Saudi Arabia. This model framework presents a clear approach for estimating the emissions generated from raw material production, the transportation of raw materials and the production process of asphalt mixtures. In other words, there is a cradle-to-gate analysis scope.
- Several computer programs and tools are available for specifically conducting LCAs of asphalt pavements. However, those programs require customization and are not directly applicable to Saudi Arabian conditions.
- Energy consumption and transport distance are two of the main factors considered when estimating GHG emissions for asphalt mix production and pavement construction. Production quantities are also important for the completion of the LCA.
- Several environmental impact categories were identified as applicable to asphalt pavements. These include climate change, photochemical ozone formation, stratospheric ozone depletion, acidification, particulate matter formation, and eutrophication.
- In general, research has shown that the use of RAP and WMA helps minimize the impact of asphalt mixtures on the environment. Thus, these two strategies are viable for further investigation.
- The use of high RAP in asphalt mixtures, as shown by the LCA demonstration results, led to a reduction in emissions (20% reduction in the case of GWP for the use of 35% RAP). This is in line with findings from the literature.

On the basis of the conclusions above, the following recommendations are provided:

- It is recommended that SAPLCA be customized by collecting pavement data from asphalt plants and other sources in Saudi Arabia.
- The customized SAPLCA is recommended for evaluating different GHG emission reduction strategies, such as high RAP and WMA, for conditions in Saudi Arabia.

# Endnotes

1 The emissions resulting from the road pavement construction, resurfacing and regular maintenance of roads are not included in the transportation emissions.

2 https://nationalhighways.co.uk/media/eispcjem/net-zero-highways-our-2030-2040-2050-plan.pdf

3 https://horizoneuropencpportal.eu/sites/default/files/2024-06/eapa-toward-net-zero-2024.pdf

4 https://www.afpa.asn.au/wp-content/uploads/2022/06/AfPA-Industry-Commitment-to-Net-Zero_Release_2022_06_09.pdf

5 https://www.asphaltpavement.org/climate/industry-goals

6 ISO 14040:2006 includes studies on life cycle inventory (LCI) and life cycle assessment (LCA). It doesn't go into great length on the LCA technique or outline the procedures for each of the LCA's phases.

7 ISO 14044:2006 standard encompasses life cycle inventory (LCI) as well as life cycle assessment (LCA) studies.

8 https://asphaltepd.org/ghg/

9 https://asphaltepd.org/

10 https://pavementlca.com/pavementlca/General/History

11 https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci

12 https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci

13 https://pre-sustainability.com/articles/recipe/

14 https://www.lcacommons.gov/lca-collaboration

15 https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci

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# Appendix A: Assessment Inventory Data

As discussed briefly in this paper, primary and secondary data types will be collected to facilitate successful completion of LCAs of asphalt pavement in Saudi Arabia. A complete description of the data required is presented in the following subsections:

**Primary Data:** These data should be collected from asphalt plants for their asphalt mixtures. The data can be collected on an annual basis (that is, over a period of 12 months) to facilitate ease of collection. The following comprises the primary data needed for the SAPLCA:

- Sum of the asphalt mixtures generated at a plant (metric tons).
- Electricity use and generation:
  - Power use in kWh, which is based on the region in which the plant is located.
  - Solar power and wind power produced on site in kWh, if any.
- Energy generator:
  - Fuel such as diesel in liters.
- Energy burner at a plant (primary or secondary)
  - The amount of natural gas used in MMBtu (1 million British thermal units).
  - Propane gas, diesel fuel, and recycled fuel used in liters.
- Energy of the asphalt binder heater:
  - Natural gas use in MMBtu.
  - Propane gas, diesel fuel, and recycled fuel used in liters.
- Energy used for mobile equipment:
  - The amount of diesel used in liters as well as the natural gas in MMBtu.
- Mix Quantities:
  - Aggregates used during production in metric tons.
  - Asphalt binder used during production in metric tons.

## Appendix A: Assessment Inventory Data

- Travel distances for transporting aggregates and asphalt binders to plants (one-way distances). This can be measured in km.
- Water used in liters at the plant.
- Stack emissions from the plant in newtons.
- General plant information:
  - Plant equipment type.
  - Equipment age.
  - Data of the most recent maintenance and location.

# Appendix B: TRACI Approach for Conducting LCIA

In the SAPLCA, the research team will utilize the TRACI method for calculating the impacts in each of the environmental categories considered. The TRACI method allows for calculating impacts via two general methods: one location-specific method and one non-location-specific method. For the SAPLCA, the team will utilize the general impact calculation method without considering the specific location where a certain chemical is being emitted. This approach considers that the location of emissions does not impact their fate, transport, or potency to any great extent. An example of such impact categories that fall within this approach is global climate change or stratospheric ozone depletion. Equation (1) below shows how the impacts are to be calculated via the selected TRACI method:

$$I^i = \sum_{xm} CF^i_{xm} \times M_{xm} \quad (1)$$

where:

$I^i$: potential impact of all chemical (x) for a specific impact category (i)
$CF^i_{xm}$: the characterization factor of chemical (x) emitted to media (m) for a specific impact category (i)
$M_{xm}$: mass of chemical (x) emitted to media (m)

With respect to the specific impact categories considered in the TRACI tool, the following points provide a brief description of each:

> Acidification: These are often air emissions that can travel far before being deposited as snow or dust particulate matter, fog, or acid rain. Thus, acidification can affect humans, buildings, paints, rivers, other water bodies, plants, and animals, and nitrogen oxides and sulfur dioxide are the major contributors to acidification.

> Eutrophication: excessive release of nitrogen and phosphorus may lead to undesirable effects in water bodies (i.e., accumulation of algal biomass).

> Global Climate Change: TRACI uses GWPs for the computation of GHG energy in relation to $CO_2$. All internationally accepted substances contributing to GWPs are considered in TRACI for this impact category.

> Ozone depletion: A lack of ozone could lead to human problems such as skin cancer. This impact category is measured via ozone depletion potentials (ODPs). The TRACI ODPs are consistent with those used by the World Meteorological Organization (WMO).

> Human health particulate matter: This category addresses particulate matter released into the ambient air. The focus is on matters that might cause negative health impacts for humans, such as respiratory diseases. Nitrogen oxides and sulfur dioxide are the most common elements that cause particulate matter.

## Appendix B: TRACI Approach for Conducting LCIA

Human Health Cancer, Noncancer, and Ecotoxicity: TRACI utilizes the global model known as USEtox for assessing the impacts of various substances (more than 3000) on human health.

Photochemical Smog Formation: Human respiratory issues can arise because ozone forms at ground level. Crop damage and other issues in ecosystems can also be affected by smog formation. Carter's maximum incremental reactivity (MIR) is used in TRACI for assessing smog formation.

Importantly, all the characterization factors for each of these categories and their substances are available on the TRACI tool website (i.e., the TRACI spreadsheet).[15] This list is not included here, as it includes more than 3000 substances.

# Notes

## About the Authors



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Ibrahem is a Senior Transport Fellow at KAPSARC with over 19 years of experience in transportation engineering. His research focuses on transport policies and technologies for decarbonizing road transport and integrated transport demand modeling to estimate energy demand and emissions. Before joining KAPSARC, Ibrahem had extensive experience across both the public and private sectors. He worked with the Department of Transport in Abu Dhabi and the Roads and Transport Authority in Dubai, as well as renowned consulting firms such as Jacobs, Michael Baker International, and Parsons Corporation. His career has spanned multiple countries, including the U.S., UAE, Jordan, and Saudi Arabia. His expertise includes public transportation fare strategies, transport policies, travel demand modeling, transportation economic impact studies, intelligent transportation systems, traffic operations, and microsimulation projects. He has served as a project manager for large-scale transportation studies and authored numerous technical reports. Ibrahem holds a B.Sc. in Civil Engineering, specializing in transportation, from Jordan University of Science and Technology in Jordan, and a Ph.D. in Civil Engineering, specializing in traffic engineering, from The University of Akron, Ohio, U.S.



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Dr. Ali serves as the Associate Director of the Center for Research and Education in Advanced Transportation Engineering Systems (CREATES) at Rowan University. He has served and continues to serve as a Principal Investigator on multiple projects funded by the Department of Defense (ERDC), the New Jersey Department of Transportation (NJDOT), the Ohio Department of Transportation (ODOT), Rhode Island Department of Transportation (RIDOT), the Federal Highway Administration (FHWA), and the Federal Aviation Administration (FAA), among other agencies. Dr. Ali has extensive expertise in the areas of laboratory and field performance characterization of flexible pavements and materials, new and innovative paving technologies, specifications and guidance development for state agencies, life cycle analysis, and decarbonization pathways of asphalt mixtures, particularly focusing on integrating reclaimed asphalt pavement (RAP) and warm-mix asphalt (WMA) technologies in asphalt mixtures. His research seeks to enhance the performance and environmental sustainability of asphalt mixtures, reducing greenhouse gas emissions, and promoting resource-efficient practices in infrastructure development.

## About the Project

This project focuses on using **life cycle assessment (LCA)** to evaluate the environmental impacts of asphalt mixtures used in roadway construction in Saudi Arabia. The aim is to develop a comprehensive LCA framework tailored to local conditions in Saudi Arabia, enabling quantitative analysis of emissions and energy use from asphalt mixtures production. As a result, the LCA model will help assess different **decarbonization pathways**, including the use of **reclaimed asphalt pavement (RAP), warm-mix asphalt (WMA)**, and alternative energy sources to reduce greenhouse gas (GHG) emissions and energy consumption across the asphalt mixture's life cycle.




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