

Article

Environmental Analysis of Emulsified Asphalt Products in the United States: A Comparative Cradle-to-Gate Life Cycle Assessment

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Abstract

Growing interest in reducing the environmental impacts of pavement preservation materials has increased the need for evaluations of emulsified asphalt. This study applies a cradle-to-gate Life Cycle Assessment (LCA) to quantify and compare the environmental profiles of four widely used cationic emulsions in the United States: CSS 1, CSS 1H, CRS 2, and CRS 2P. The assessment incorporates primary data collected from 17 manufacturing plants across different regions, supported by information from suppliers and secondary datasets from the 2023 GaBi database. Impact calculations were performed using GaBi software, and sensitivity analyses were conducted to determine which formulation components most influence the results. Environmental impact categories in the study include global warming potential (GWP), particulate matter (PM_{2.5}), photochemical ozone creation potential (POCP), and renewable and nonrenewable primary energy demand. The findings show that rapid-setting emulsions (CRS 2 and CRS 2P) generally exhibit lower environmental burdens than slow-setting emulsions (CSS 1 and CSS 1H). Differences in asphalt binder content, emulsifier dosage, and latex additions were identified as major contributors to environmental performance. By identifying key drivers of environmental impact, this study supports more sustainable material choices in pavement preservation. The results provide updated industry-specific LCA benchmarks for emulsified asphalt and highlight opportunities for environmental improvement through targeted adjustments to product formulations.

Keywords: life cycle assessment; emulsified asphalt; asphalt binder; pavement; sustainability



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1. Introduction

The main constituents of emulsified asphalt include asphalt binder, emulsifying agent, and water, while additives like latex and hydrochloric acid (HCl) may also be incorporated [1–3]. In this manuscript, the term *asphalt binder* follows US usage and refers to the petroleum-based material commonly known as bitumen in European and other international contexts. Asphalt binder is considered the main constituent of emulsified asphalt, functioning as the cohesive agent that binds aggregate particles together and significantly influences the mechanical and durability performance of the mixture [4]. Asphalt binder undergoes ageing during its service life, primarily through thermal-oxidative processes that lead to increased stiffness and reduced ductility [5].

In addition to asphalt binder, emulsified asphalt consists of several auxiliary components that play essential roles in ensuring stability and workability during production and application. Although drinking water is commonly used in emulsified asphalt production, its quality must be controlled [6,7]. This is because certain impurities, even within potable standards can adversely affect emulsion stability and performance [6,8–10]. Beyond water quality considerations, in cationic emulsified asphalts, pH levels are typically regulated using substances such as HCl and phosphoric acid [11]. When combined with compatible asphalt, clean water, and adequate mechanical energy, the emulsifying agent plays the most critical role in determining emulsification quality and performance in the field [12]. Emulsified asphalt is categorized as either cationic or anionic depending on the type of emulsifying agent used, corresponding to positive and negative charges, respectively [1,13]. Compared with anionic and nonionic emulsified asphalt, cationic emulsified asphalt exhibits faster breaking behavior, improved adhesion, and superior compatibility with acidic aggregates. These characteristics make it particularly suitable for applications such as tack coats, chip seals, slurry seals, and cold recycling technologies. Moreover, the enhanced bonding performance of cationic emulsified asphalt contributes to improved early strength development and moisture resistance, which are critical for pavement durability [9,14]. In addition to charge type, emulsified asphalts are categorized by how quickly they set: rapid, medium, or slow [2]. Each setting category has specific characteristics that influence its effectiveness in different construction contexts [1,13]. Emulsified asphalt is essential in the development and upkeep of infrastructure such as highways, airport runways, and parking areas. Emulsified asphalt is frequently applied in pavement construction for both tack coat and prime coat treatments. Compared to conventional asphalt materials, emulsified asphalt provides benefits including better workability, lower energy use, and improved environmental performance in specific applications. Emulsified asphalt enables the production of cold mix asphalt (CMA), allowing road construction to proceed continuously without relying on hot mix asphalt (HMA) facilities. More significantly, it plays a central role in pavement preservation strategies such as micro-surfacing, slurry sealing, and chip sealing, all of which contribute to prolonging the service life of existing pavements [15].

One of the environmental benefits of emulsified asphalt is its lower production temperatures, which result in reduced energy demand and associated greenhouse gas outputs [16,17]. Recycling existing pavement using emulsified asphalt supports sustainable construction by reducing the need for virgin material inputs [13]. While the benefits of emulsified asphalt are well recognized, few LCAs and Environmental Product Declarations (EPDs) have been developed to quantify its environmental performance, which are necessary to enhance existing environmental impact assessments. Recent studies have explored strategies to improve the sustainability of asphalt materials through material selection and production practices [18,19].

LCA is a thorough method for assessing sustainability [20]. It is used to evaluate the environmental effects associated with a given product or process. In LCA, environmental metrics like energy usage, resource consumption, and environmental emissions are quantified for a given product or process. Keeping the Life Cycle Inventory consistent and current (LCI) database remains a key challenge when evaluating the environmental impacts of transportation infrastructure decisions. The primary advantage of LCA is its systematic approach, which allows for the assessment of environmental impacts over an extended time frame. When LCA is applied to emulsified asphalt, it facilitates comparisons with other materials, helps identify process inefficiencies, increases clarity for stakeholders, aids strategic planning, and encourages continual improvements in environmental performance.

Numerous researchers have employed LCA methods along with various datasets to examine the environmental effects associated with both rigid and flexible pavement types.

The Eurobitume inventory data have been frequently used as a key input in LCA studies, creating a representative model of a refinery in northern Europe [21]. Similarly, North American petroleum refinery LCA models adopt an average crude slate approach. This is illustrated through tools like the Thinkstep refinery framework within GaBi [22] and the LCI Model for petroleum refineries [23].

In 2022, researchers developed pavement life cycle inventories for the California Department of Transportation (Caltrans) [24]. Because US-specific data were limited, they obtained emulsified asphalt LCI data from the Eurobitume data and built a model using GaBi.

International Organization for Standardization (ISO) [25] defines LCA as a process that includes four key stages: setting the study objective and scope, compiling the LCI, evaluating impacts through LCIA, and analyzing the outcomes for interpretation. Decision-makers can use LCA as a structured analytical tool to quantitatively examine how transportation systems affect the environment, both through immediate and long-term pathways [26]. Because road infrastructure requires significant materials and energy over its long lifespan, it is critical to identify strategies that reduce its environmental impact across all life cycle stages [27]. Although LCA is widely applied across multiple sectors, its use in the planning phase is still uncommon and requires deeper exploration to understand its full potential [28].

This paper presents a comparative LCA for different types of cationic emulsified asphalt used in the US. The research evaluates selected cationic slow-setting and rapid-setting emulsions, including both standard and polymer-modified formulations (CSS-1H, CSS-1, CRS-2, CRS-2P). As part of a sensitivity analysis, the relative environmental impacts of these emulsions are compared, highlighting significant influence of latex, emulsifying agent, and asphalt binder on the overall impact.

The analysis utilizes data from 17 emulsified asphalt manufacturing sites located in multiple states across the U.S. Due to confidentiality agreements with industry partners, the exact locations and names of these facilities cannot be disclosed. However, the selected facilities represent a diverse range of operational conditions and geographic locations, ensuring that the study captures variations in production practices.

While facility size was not explicitly controlled as a selection criterion, the dataset includes plants with varying production scales, with annual emulsified asphalt production in 2023 ranging from 2426 to 7889 kilogallons (approximately 9.2 to 29.9 million liters). This approach ensures that the results provide a broad perspective on the ecological impact of emulsified asphalt production. Although LCA has been widely applied to asphalt pavements and mixtures, studies specifically evaluating the cradle-to-gate environmental impacts of emulsified asphalt, particularly in the US, remain limited. This study addresses this gap by providing a cradle-to-gate LCA of commonly used cationic emulsified asphalts based on plant-specific primary data. The intent is to facilitate decision-making processes and advance the creation of EPD for emulsified asphalt.

2. Goal and Scope of the Study

LCA begins by clearly outlining its goal and scope, which frames the system limits, defines the analysis period, and establishes the declared unit for comparison. In this research, the primary objective was to assess how the production processes of different emulsified asphalts contribute to environmental impacts within the US.

The analysis considers processes from resource extraction through to the factory gate, encompassing production stages and the transport of inputs. In cases where the final use or function of a product remains undefined, studies typically rely on a declared unit rather than a functional unit to maintain consistency in environmental comparisons [20]. This analysis

uses the production of a single tonne of emulsified asphalt as the declared unit, representing the final product as it leaves the manufacturing facility. Given the variability in emulsified asphalt types, including differences in asphalt content, emulsifying agent composition, and intended applications, this unit ensures comparability across different types. The study accounts for variations in emulsion formulations by including multiple commonly used emulsified asphalt types and analyzing their respective environmental impacts.

The study targets a diverse audience, including government agencies, policymakers, pavement engineers, sustainability experts, and academic researchers. As shown in Figure 1, the declared unit of one metric ton of emulsified asphalt establishes a consistent reference basis for LCA. This unit enables the normalization of material inputs, energy use, transportation, and associated emissions. By adopting a declared unit rather than a functional unit, the analysis ensures comparability among emulsified asphalt types with different formulations and applications and provides the basis for the cradle-to-gate (A1–A3) life cycle inventory and impact assessment [25].

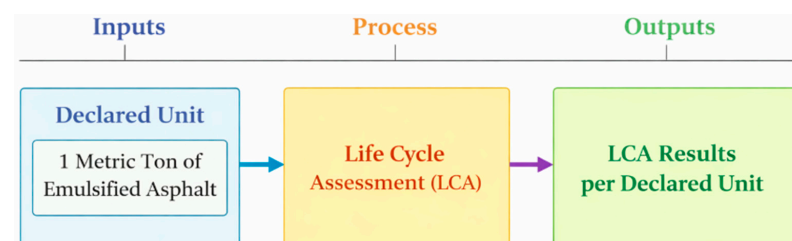


Figure 1. Defined declared unit.

Figure 2 illustrates the main production stages of emulsified asphalt within a cradle-to-gate (A1–A3) system boundary, including raw material acquisition (A1), transportation of inputs (A2), and plant manufacturing (A3). The environmental pollution and impact categories associated with each stage, such as greenhouse gas emissions, particulate matter, photochemical ozone formation, and primary energy demand, are quantified through the life cycle inventory and reported by stage in Sections 3 and 4.

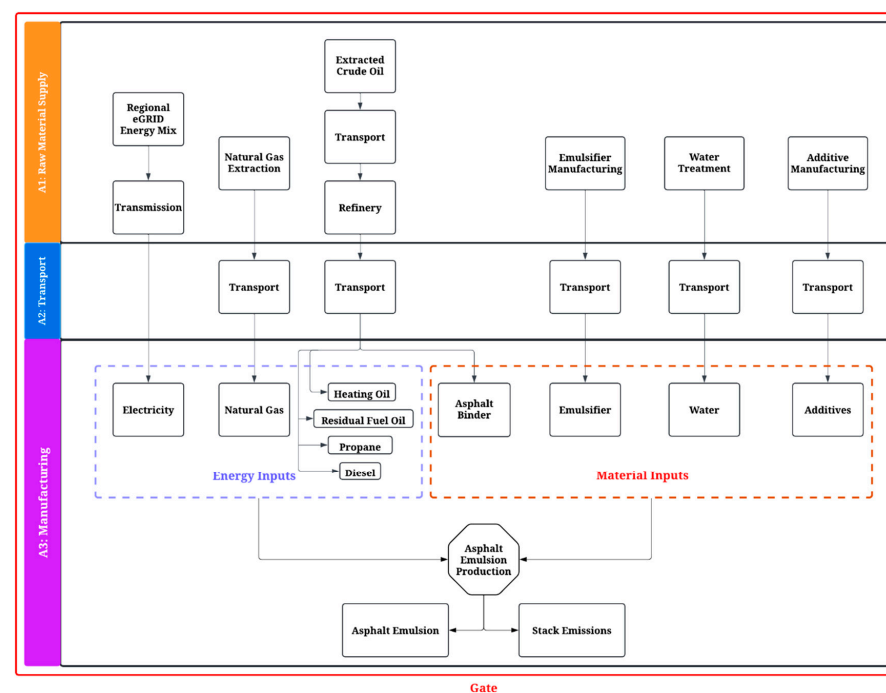


Figure 2. Process flowchart for emulsified asphalt production (cradle-to-gate). Adopted from [29].

3. LCI and LCIA

LCI focuses on measuring the key resource inputs and environmental outputs linked to a product or process across all phases of its life cycle [30]. It was introduced in the 1960s as a tool to support cleaner production practices and has since seen extensive application in both industrial and academic contexts [31,32]. The inventory stage systematically tracks all resource inputs and environmental outputs confined within the life cycle's system boundary. This includes the intake of energy and raw materials, alongside the release of emissions, waste streams, and usable product outputs. At this point, researchers compile and assess detailed data to represent the full set of exchanges across the system. Figure 3 visualizes the structure of the LCI methodology.

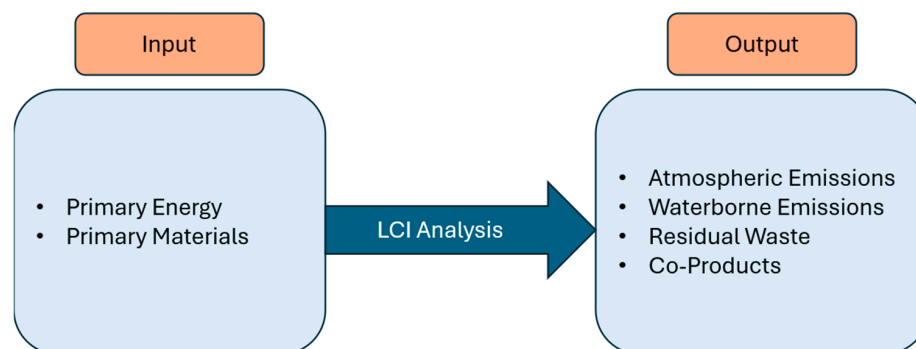


Figure 3. LCI methodology.

LCIA translates inventory data into quantifiable indicators that illustrate how a product or system affects environmental quality and human well-being [26]. The LCIA process consists of two primary stages:

- **Classification:** In this phase, items from the LCI are grouped into relevant environmental impact categories based on the specific type of damage they contribute to. These categories often include acidification, eutrophication, human toxicity, ozone depletion, and GHG emissions.
- **Characterization:** Here, numerical values or weighting factors are applied to the categorized data, quantifying the magnitude of each impact and reflecting the overall environmental burden associated with the product or process life cycle.

To date, no globally preferred LCIA approach exists that can reliably and consistently translate LCI outputs into meaningful estimates of ecological or environmental consequences [25]. Numerous frameworks, including TRACI [33], ReCiPe [34], CML [35], and Eco-indicator 99 [36], have been developed and refined over time. In addition, newer tools such as LC-Impact [37] are increasingly being acknowledged within the field. These approaches are typically categorized as midpoint, endpoint, or hybrid methods. Endpoint models estimate the ultimate damage resulting from emissions or resource use, such as impacts on ecosystems or human health. In contrast, midpoint models focus on earlier stages in the cause–effect pathway, generating indicators tied to specific environmental mechanisms before reaching final outcomes [26]. Impact categories cover an extensive spectrum, ranging from general themes to more narrowly defined environmental issues. Examples include global warming, mineral depletion, land use, acidification, nonrenewable energy use, noise pollution, biodiversity decline, aquatic and terrestrial toxicity, ionizing radiation, eutrophication, photo-oxidant formation, and impacts on human and ecosystem health. This broad array reflects the complexity of environmental challenges evaluated in impact assessments and highlights the variety of factors taken into account [38,39].

This study adopts TRACI 2.1 as its chosen impact assessment framework, a widely used LCA method for quantifying the environmental burdens associated with products

and processes. TRACI 2.1 was developed by the US Environmental Protection Agency and incorporates characterization factors representative of United States environmental conditions, making it well suited for evaluating the environmental impacts of emulsified asphalt production within the US context [40–42].

A range of environmental categories was chosen for LCIA in this research, including the following:

- Global Warming Potential (GWP): Expressed in kilograms of CO₂ equivalent (kg CO₂-eq), GWP reflects the climate impact of greenhouse gas emissions over a 100-year horizon, based on characterization factors from the IPCC's Fifth Assessment Report (AR5), which is widely adopted as the GWP100 metric [21].
- Photochemical Ozone Creation Potential (POCP): Represented in kilograms of ozone equivalent (kg O₃-eq) using TRACI, this category quantifies the contribution of emissions to ground-level ozone (smog) generation, also known as smog formation potential (SFP).
- Human Health (PM_{2.5}): Expressed in kilograms of PM_{2.5}, this metric quantifies the emission of fine airborne particles with diameters of 2.5 µm or less, which are harmful to human health when inhaled.
- Nonrenewable Primary Energy Demand: Reported in megajoules (MJ), this metric accounts for the net calorific energy extracted from fossil fuels and other nonrenewable sources, excluding feedstock contributions.
- Renewable Primary Energy Demand: Also measured in MJ, this refers to the usable energy obtained from renewable sources such as biomass, wind, or solar, again excluding feedstock energy.

Numerous tools exist for conducting pavement-related LCA, such as SimaPro (<https://simapro.com/>), GaBi, DuboCalc (<https://www.dubocalc.nl/en/>), and the LCA Pave Tool (<https://www.fhwa.dot.gov/pavement/lcatool/>, accessed on 20 August 2025) [43,44]. In this study, GaBi software (version 10.7.1) was used to conduct the LCA of emulsified asphalt, a software widely applied in both the US and Europe.

3.1. Selected Types of Emulsified Asphalt

The classification of emulsified asphalt is determined by its underlying chemical characteristics, setting rates, and specific modifications, which help in identifying its suitable applications in road construction and maintenance. The main categories are anionic and cationic emulsions. Anionic emulsions do not have the letter “C” before the emulsion type, such as RS-1, whereas cationic emulsions do, such as CRS-1 [9]. Setting behavior is categorized using labels such as RS (Rapid-Setting), QS (Quick-Setting), MS (Medium-Setting), and SS (Slow-Setting), which describe how quickly the emulsion will break or set after being applied. The numbers following these letters, either 1 or 2, signify the viscosity level, with 1 representing lower viscosity and 2 indicating higher viscosity. Additional letters such as “H” indicate harder base asphalt, and “HF” denotes high-float emulsions, which have additives to create a thicker asphalt film on aggregates. As an example, CSS 1 refers to a cationic slow-setting emulsified asphalt with low viscosity, while CRS 2 designates a cationic rapid-setting type known for its high viscosity. CMS 2H indicates a cationic medium setting emulsion that combines high viscosity with a harder base asphalt. Standard classifications recognized by ASTM and AASHTO include several anionic types such as RS 1 and RS 2, as well as cationic types like CRS 1 and CRS 2. Emulsions modified with polymers often include additional letters such as P, S, or L in their names, as seen in CRS 2P, and offer improved performance characteristics.

To identify suitable emulsified asphalt products for this analysis, specifications from all 50 state Departments of Transportation were reviewed. Fourteen cationic emulsified

asphalt types were selected based on this evaluation: CRS 1, CMS 2RA, CQS 1H, CSS 1H, CRS 2, CRS 2P, CMS 2, CRS 2H, CMS 2S, CRS 2R, CMS 2H, CSS 1, CQS 1, and CRS 1H.

The goal was to determine which three cationic emulsified asphalt types are most frequently specified across state transportation agencies. Figure 4 presents the frequency with which each selected emulsion is referenced in the specifications of various State DOTs.

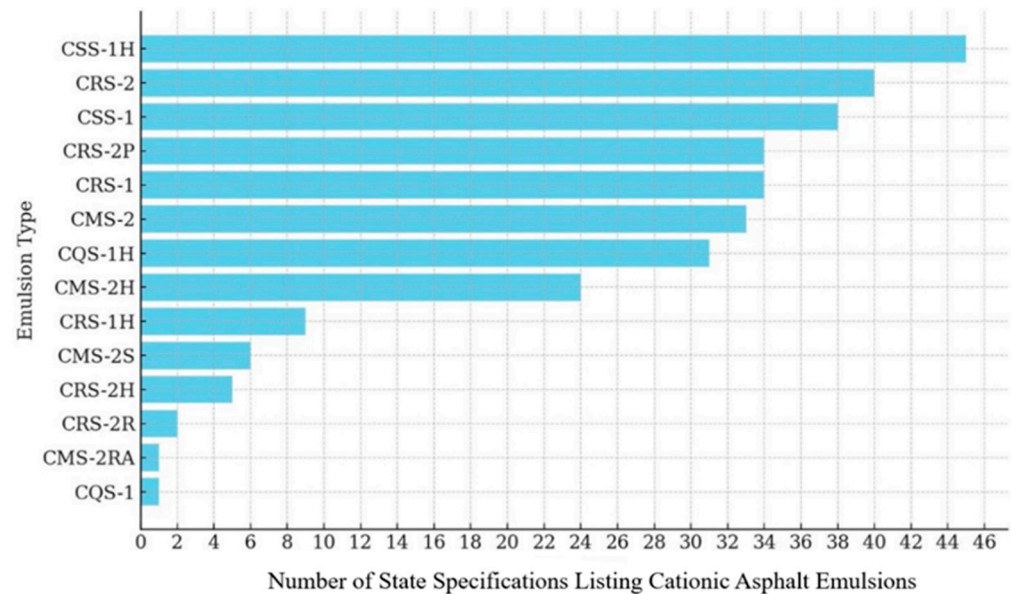


Figure 4. Distribution of cationic emulsion usage in state DOT specifications.

Table 1 highlights CSS 1H, CRS 2, and CSS 1 as the most commonly specified emulsified asphalt types across state DOT standards. To facilitate a comparative LCA between unmodified and polymer-enhanced cationic emulsions, CRS 2P was also included as a fourth selected product. Emulsified asphalt types are defined according to standard ASTM and AASHTO classifications commonly adopted in US Department of Transportation specifications [45,46].

Table 1. Emulsified asphalt production at individual facilities. Adopted from [29].

Emulsified Asphalt Production Facility	Type of Emulsified Asphalt Produced				
A	CRS-2	–	–	–	–
B	CRS-2	CSS-1	CSS-1H	CRS-2P	–
C	CRS-2	–	CSS-1H	CRS-2P	–
D	CRS-2	–	–	CRS-2P	–
E	CRS-2	–	–	CRS-2P	–
F	CRS-2	–	–	–	–
G	–	–	CSS-1H	–	–
H	CRS-2	–	–	–	–
I	CRS-2	CSS-1	–	CRS-2P	–
J	–	–	CSS-1H	–	–
K	–	–	CSS-1H	–	–
L	CRS-2	–	CSS-1H	CRS-2P	–
M	–	–	–	CRS-2P	–
N	CRS-2	–	CSS-1H	CRS-2P	–
O	CRS-2	–	–	–	–
P	–	CSS-1	–	CRS-2P	–
Q	CRS-2	–	CSS-1H	CRS-2P	–
No. of facilities	12	3	8	10	–

– Production not carried out at this site.

3.2. Presence of Chosen Emulsified Asphalt Types Across Supplier Locations

While individual production sites manufacture a range of emulsified asphalt types, this study concentrates on a predefined subset. Table 1 outlines how the selected emulsified asphalt products are distributed among the 17 facilities included in the analysis.

3.3. Data Compilation for LCI

Information was obtained from 17 emulsified asphalt production facilities. The data collection process from each site covered a wide scope of details, including the following: (1) types of emulsified asphalt produced; (2) quantity manufactured and the corresponding energy consumption for each type; (3) formulation details such as material proportions and individual components; (4) ingredient breakdowns for latexes and emulsifying agents; and (5) transport distances for raw inputs such as emulsifying agents, asphalt binder, hydrochloric acid, latex, and softener to their respective production sites.

This study incorporates both primary and secondary sources of data. Primary data were directly obtained from emulsified asphalt producers for the purposes of this research, while secondary data were drawn from the GaBi database and published literature. Since each facility produces emulsified asphalt with unique formulations and material ratios, a separate model was constructed in GaBi for every case. All energy-related information associated with emulsified asphalt production was supplied by the respective manufacturers.

Detailed information gathered from emulsified asphalt production sites, including material formulations, operational data, and transportation logistics, is considered proprietary and is protected under confidentiality agreements with industry collaborators. Although specific values cannot be released, the LCA framework used in this study can be replicated in future research by utilizing publicly accessible data sources for comparative analysis.

The types of data used for each emulsified asphalt component and related energy inputs are categorized as either primary or secondary, as detailed below.

1. Raw Material Inputs:

- Binder: Secondary data referencing the Asphalt Institute's report for the North American region.
- Emulsifying Agents: Based on primary data gathered from supplier-provided safety data sheets (SDSs).
- Additive Agents: Based on primary data gathered from supplier-provided SDSs.
- Water: Obtained as secondary data from the GaBi LCI database.
- Hydrochloric acid: Sourced from the same secondary database as water.

2. Energy Inputs:

- Natural Gas: Primary figures directly reported by emulsified asphalt producers.
- Electricity: Also based on primary data obtained from those same industry partners.

With the exception of water, which is delivered through pipelines, all raw materials are transported to their destination facilities using heavy-duty trucks. To evaluate the environmental footprint of this transport activity, the functional unit was defined as 1000 kg-km. In other words, the model evaluates the emissions and resource use resulting from the movement of one metric ton of material across a one-kilometer distance. For every production site, the transportation-related environmental burden was calculated by multiplying the distance from each material supplier to the respective emulsified asphalt facility by the impact value assigned to the functional unit. These transport distances vary by both material type and facility location. All transport-related distance data were provided directly by the emulsified asphalt manufacturers.

4. LCIA Results

A total of 33 emulsified asphalt variants, distributed across four types, were examined across 17 production sites through individual LCIA modeling. Each formulation was assigned to its own GaBi model to quantify its corresponding environmental footprint.

4.1. Resource Acquisition and Plant Manufacturing Stages

Table 2 compares the environmental performance of various emulsified asphalt formulations across multiple facilities, focusing on the resource acquisition and manufacturing stages. To comply with confidentiality agreements, absolute values for impact indicators are not disclosed. Instead, results are expressed as percentages relative to a designated baseline. This normalized presentation is based on consistent plant-specific primary data and a uniform life cycle inventory and impact assessment framework. The CRS 2 output from Facility B is used as the reference point, set at 100 percent, with all other results scaled accordingly. CRS 2 was selected as the baseline due to its consistently lower environmental burden among the evaluated emulsions. Facility B was selected as the reference site since it is the only location that produces all four emulsified asphalt types, providing a consistent basis for internal comparison. This setup enables a clear evaluation of performance differences among the various formulations. By using a single facility that produces all investigated products, differences in environmental impacts can be primarily attributed to formulation characteristics rather than facility-specific operational or regional factors. The percentage variation from the reference highlights whether a given emulsion has a higher or lower environmental footprint per metric ton produced. Overall, this method offers a comparative view of how formulation differences and facility-specific characteristics influence environmental outcomes, while preserving data confidentiality. Variations in emulsifiers, stabilizers, and pH regulators among production facilities are reflected in the raw material stage results through plant-specific formulation data, and their environmental influence is further quantified in the sensitivity analysis presented in Section 5.

Table 2. Comparative analysis of emulsified asphalt impacts in resource acquisition and plant manufacturing stages. Adopted from [29].

Facility	Emulsified Asphalt Type	GWP	POCP	PM _{2.5}	PED (Renewable)	PED (Non-Renewable)
A	CRS-2	98%	97%	99%	106%	98%
B	CSS-1	114%	112%	103%	167%	99%
	CSS-1H	114%	112%	103%	167%	99%
	CRS-2	100%	100%	100%	100%	100%
	CRS-2P	113%	105%	103%	142%	103%
C	CSS-1H	112%	110%	101%	164%	96%
	CRS-2	97%	98%	99%	91%	98%
	CRS-2P	98%	98%	98%	96%	98%
D	CRS-2	101%	100%	100%	119%	99%
	CRS-2P	111%	103%	103%	148%	102%
E	CRS-2	104%	104%	105%	98%	105%
	CRS-2P	115%	108%	108%	130%	108%
F	CRS-2	96%	97%	98%	89%	97%
G	CSS-1H	117%	114%	103%	183%	99%
H	CRS-2	95%	96%	97%	88%	97%

Table 2. Cont.

Facility	Emulsified Asphalt Type	GWP	POCP	PM _{2.5}	PED (Renewable)	PED (Non-Renewable)
I	CSS-1	113%	111%	100%	175%	94%
	CRS-2	98%	99%	100%	90%	100%
	CRS-2P	99%	100%	102%	92%	101%
J	CSS-1H	116%	112%	102%	193%	95%
K	CSS-1H	118%	113%	104%	210%	99%
L	CSS-1H	124%	120%	108%	221%	101%
	CRS-2	100%	98%	99%	115%	100%
	CRS-2P	114%	103%	103%	159%	103%
M	CRS-2P	111%	102%	102%	147%	101%
N	CSS-1H	112%	110%	101%	167%	97%
	CRS-2	98%	98%	98%	94%	99%
	CRS-2P	113%	105%	104%	135%	104%
O	CRS-2	93%	93%	94%	91%	94%
P	CSS-1	130%	127%	110%	230%	101%
	CRS-2P	106%	102%	102%	120%	101%
Q	CSS-1H	129%	126%	109%	233%	99%
	CRS-2	97%	97%	98%	99%	96%
	CRS-2P	105%	102%	101%	122%	100%

Interpreting the results requires an understanding of the broader context for each environmental impact category. As outlined in ISO 14044 [47], the relevance of different impact categories depends on baseline levels, regulatory limits, and specific environmental conditions. For instance, a two percent rise in GWP may indicate a minor shift in long-term climate influence, whereas an equivalent increase in PM_{2.5} or POCP could result in more immediate and localized consequences, particularly in terms of air pollution and public health. Therefore, assessing the relative weight of each category involves considering both the scale of its impact and the potential severity of its effects. Regardless of the specific emulsification equipment or production technique employed at each facility, their influence on environmental performance is inherently reflected in the facility-specific primary data used in this study, including measured energy consumption and material input quantities.

4.2. Transportation Stage

The total transportation impact for each emulsified asphalt product was determined by summing the individual transport contributions of all its constituent materials. Transportation impacts were modeled using standardized heavy-duty diesel truck transportation processes implemented in the GaBi life cycle assessment software [48,49]. Fuel consumption parameters and emission factors were obtained from the GaBi life cycle inventory database and are representative of United States operating conditions. These transportation modeling assumptions were applied consistently across all evaluated facilities and raw materials to ensure methodological consistency and comparability of transportation-related environmental impacts.

To ensure consistency with the material sourcing and manufacturing stages, the transportation result for CRS 2 from Facility B was selected as the baseline, set at 100 percent. All other values were scaled relative to this benchmark. The analysis compares transportation impacts for all evaluated emulsified asphalt types, as shown in Table 3. The observed variation in relative transportation impacts is primarily driven by differences

in hauling distances and facility locations, which influence raw material sourcing and delivery requirements.

Table 3. Comparative analysis of emulsified asphalt impacts in transportation stage. Adopted from [29].

Facility	Emulsified Asphalt Type	GWP	POCP	PM _{2.5}	PED (Renewable)	PED (Non-Renewable)
A	CRS-2	146%	145%	145%	100%	145%
B	CSS-1	106%	105%	105%	100%	105%
	CSS-1H	106%	105%	105%	100%	105%
	CRS-2	100%	100%	100%	100%	100%
	CRS-2P	103%	103%	103%	100%	103%
C	CSS-1H	93%	93%	93%	100%	93%
	CRS-2	85%	84%	84%	100%	84%
	CRS-2P	94%	94%	94%	100%	94%
D	CRS-2	14%	14%	14%	100%	14%
	CRS-2P	22%	22%	22%	100%	22%
E	CRS-2	7%	7%	7%	100%	7%
	CRS-2P	17%	17%	17%	100%	17%
F	CRS-2	32%	32%	32%	100%	32%
G	CSS-1H	702%	700%	699%	100%	700%
H	CRS-2	137%	137%	137%	100%	137%
I	CSS-1	89%	89%	89%	100%	89%
	CRS-2	89%	89%	89%	100%	89%
	CRS-2P	91%	91%	91%	100%	91%
J	CSS-1H	115%	115%	115%	100%	115%
K	CSS-1H	909%	910%	910%	100%	911%
L	CSS-1H	10%	10%	10%	100%	10%
	CRS-2	6%	6%	6%	100%	6%
	CRS-2P	19%	19%	19%	100%	19%
M	CRS-2P	49%	49%	49%	100%	49%
N	CSS-1H	123%	122%	123%	100%	122%
	CRS-2	118%	118%	118%	100%	118%
	CRS-2P	122%	122%	121%	100%	122%
O	CRS-2	774%	771%	771%	100%	771%
P	CSS-1	408%	409%	408%	100%	408%
	CRS-2P	389%	388%	388%	100%	387%
Q	CSS-1H	186%	186%	185%	100%	186%
	CRS-2	148%	147%	147%	100%	147%
	CRS-2P	156%	156%	156%	100%	156%

Overall, transportation was found to be a relatively minor contributor to the total cradle-to-gate environmental impacts of emulsified asphalt, a trend that is further summarized in Section 7.

4.3. Resource Acquisition, Plant Manufacturing, and Transportation Stages

By integrating findings from the transportation stage and the resource acquisition and plant manufacturing stages, this section provides a complete LCIA assessment of emulsified

asphalt across the full cradle-to-gate scope. The consolidated outputs are presented in Table 4.

Table 4. Comparative analysis of emulsified asphalt impacts in all stages. Adopted from [29].

Facility	Emulsified Asphalt Type	GWP	POCP	PM _{2.5}	PED (Renewable)	PED (Non-Renewable)
A	CRS-2	99%	101%	102%	106%	98%
B	CSS-1	114%	112%	104%	167%	99%
	CSS-1H	114%	112%	104%	167%	99%
	CRS-2	100%	100%	100%	100%	100%
	CRS-2P	113%	105%	103%	142%	103%
C	CSS-1H	111%	109%	101%	164%	96%
	CRS-2	97%	97%	98%	91%	98%
	CRS-2P	98%	97%	98%	96%	98%
D	CRS-2	99%	94%	95%	119%	99%
	CRS-2P	108%	97%	98%	148%	102%
E	CRS-2	101%	97%	98%	98%	104%
	CRS-2P	112%	101%	102%	130%	108%
F	CRS-2	94%	92%	94%	89%	97%
G	CSS-1H	133%	159%	141%	183%	102%
H	CRS-2	96%	99%	99%	88%	97%
I	CSS-1	112%	109%	99%	175%	94%
	CRS-2	98%	98%	100%	90%	100%
	CRS-2P	99%	99%	101%	92%	101%
J	CSS-1H	116%	112%	103%	193%	95%
K	CSS-1H	140%	174%	156%	210%	103%
L	CSS-1H	121%	112%	101%	221%	101%
	CRS-2	97%	91%	94%	115%	99%
	CRS-2P	111%	97%	98%	159%	103%
M	CRS-2P	109%	98%	98%	147%	100%
N	CSS-1H	112%	111%	103%	167%	97%
	CRS-2	98%	99%	100%	94%	99%
	CRS-2P	113%	106%	105%	135%	104%
O	CRS-2	113%	145%	137%	91%	98%
P	CSS-1	138%	148%	129%	230%	103%
	CRS-2P	114%	124%	120%	120%	103%
Q	CSS-1H	131%	131%	114%	233%	100%
	CRS-2	98%	101%	101%	99%	97%
	CRS-2P	107%	106%	105%	122%	100%

4.4. LCIA Comparative Results for Selected Emulsified

This study examined four emulsified asphalt formulations: CRS 2, CSS 1, CSS 1H, and CRS 2P. Among the 17 facilities analyzed, some produced the full set of four types, while others were limited to three, two, or just one. Altogether, the dataset included 33 distinct emulsified asphalt products, distributed as follows: 12 for CRS 2, 3 for CSS 1, 8 for CSS 1H, and 10 for CRS 2P. Figure 5 compares the average environmental performance across key impact categories for each formulation. CRS 2, having shown the lowest total impact across all categories, was selected as the benchmark for comparison.

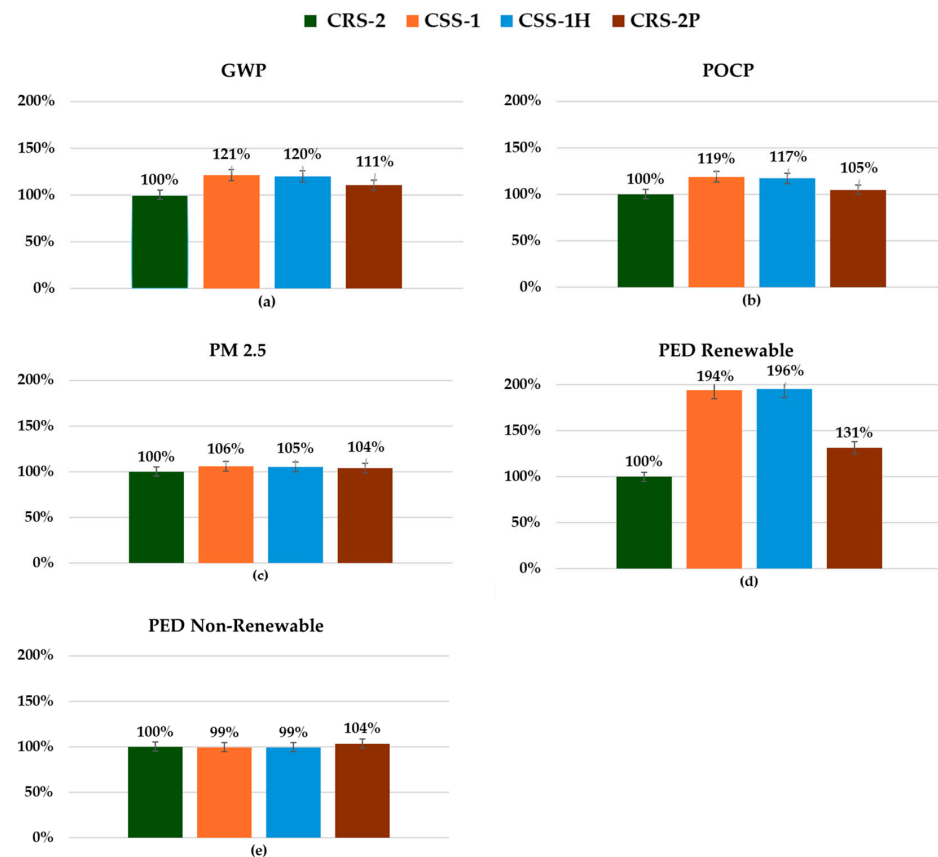


Figure 5. Comparison of average environmental performance across key impact categories for each formulation, including: (a) Global Warming Potential (GWP), (b) Photochemical Ozone Creation Potential (POCP), (c) Particulate Matter (PM_{2.5}), (d) Renewable Energy Demand, and (e) Nonrenewable Energy Demand. Panels (a–e) are presented together to facilitate comparison across impact categories while avoiding redundancy.

The observed trends and differences among emulsified asphalt types and life cycle stages are further interpreted and discussed in Section 6, where the main drivers of environmental impacts are explained based on material composition, energy use, and sensitivity analysis results.

5. Sensitivity Analysis

This section explores how variations in individual components affect the total LCIA outputs for emulsified asphalt. The objective is to evaluate the system's responsiveness to changes in input variables and to determine which parameters have the greatest influence on environmental outcomes. To achieve this, input values were systematically adjusted within a controlled range, and the respective shifts in result were analyzed. The method used was a one variable at a time approach, where a single parameter was modified while all others remained fixed. Each variable was altered across five intervals, specifically at minus ten, minus five, zero, plus five, and plus ten percent. This one-at-a-time approach was adopted to quantify marginal environmental effects of individual inputs; potential interaction effects among formulation components are acknowledged but were considered beyond the scope of the present environmental life cycle assessment. This analysis used the CSS-1H from Facility Q as the representative case. CSS-1H was selected as the case representative because it is the most widely specified emulsified asphalt across U.S. state DOT standards. Seven input parameters were examined: emulsifying agent, asphalt binder, water, hydrochloric acid, latex, electricity from eGRID, and natural gas. This resulted in thirty-five separate evaluations, one for each input level across the seven

variables. The environmental impacts were then analyzed for selected categories. The results showed consistent linear trends, meaning that the effect of any percentage change in each component could be predicted using a corresponding equation. The normalized sensitivity response was calculated as the percentage change in environmental impact relative to the baseline (0%) case according to:

$$R_i(\%) = \frac{I(x_i + \Delta x_i) - I(x_i)}{I(x_i)} \times 100$$

where $I(x_i)$ is the baseline life cycle impact result, $I(x_i + \Delta x_i)$ is the impact result obtained after applying a perturbation Δx_i to input x_i (−10%, −5%, +5%, +10%) while holding all other inputs constant, and R_i represents the normalized sensitivity response.

To illustrate these trends, Figure 6 shows the impact of increasing each component's weight by five percent while all other variables remain unchanged.

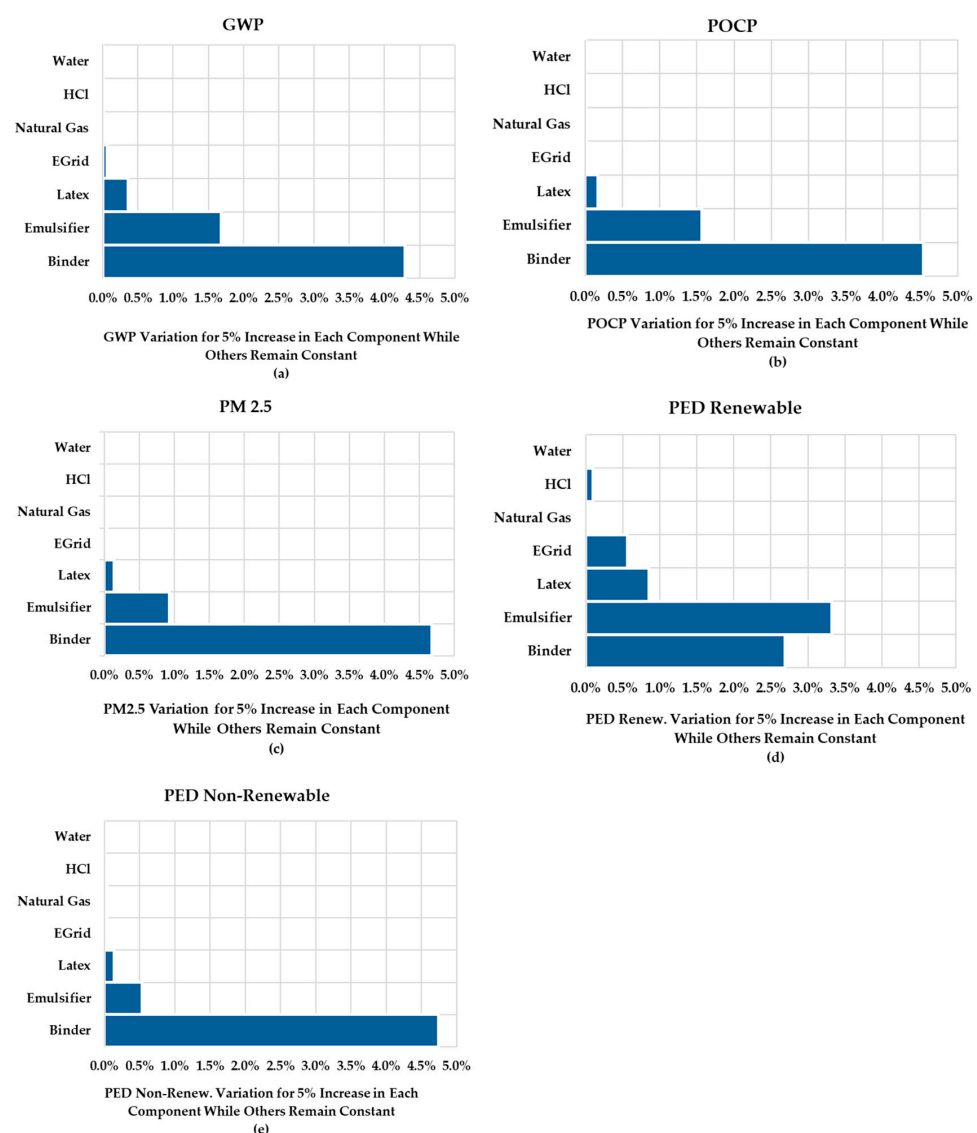


Figure 6. Sensitivity of Environmental Impact Metrics to Input Variations: (a) Global Warming Potential (GWP), (b) Photochemical Ozone Creation Potential (POCP), (c) Particulate Matter (PM_{2.5}), (d) Renewable Energy Demand, and (e) Nonrenewable Energy Demand. Panels (a–e) are presented together to facilitate comparison across impact categories while avoiding redundancy.

Figure 6 clearly shows that asphalt binder has the strongest influence on impact outputs, followed by emulsifying agent and latex. The remaining components contributed significantly less by comparison to the three most influential materials. The significant contribution of emulsifying agents to renewable primary energy demand, as shown in Figure 6d, is primarily linked to their material makeup. While asphalt binder is derived from fossil sources, emulsifying agents often include ingredients such as plant oils or bio-based fatty acids. This reliance on renewable feedstocks results in a higher energy demand attributed to renewable sources. Their distinct composition accounts for the elevated impact observed in this category relative to other components [29,50].

It is important to note that the initial comparisons are based on the mass contribution of each material. For instance, asphalt binder typically makes up around 60 percent of the total mass in one metric ton of emulsified asphalt, while emulsifying agent content is generally below 2 percent. To isolate the influence of each component from its relative quantity, a separate analysis was conducted that evaluates sensitivity on a per-kilogram basis. This approach examines the change in environmental impact caused by adding one kilogram of each individual material, regardless of its original proportion. Figure 7 presents the results, showing how each impact category responds to a one-kilogram increase in a specific component.

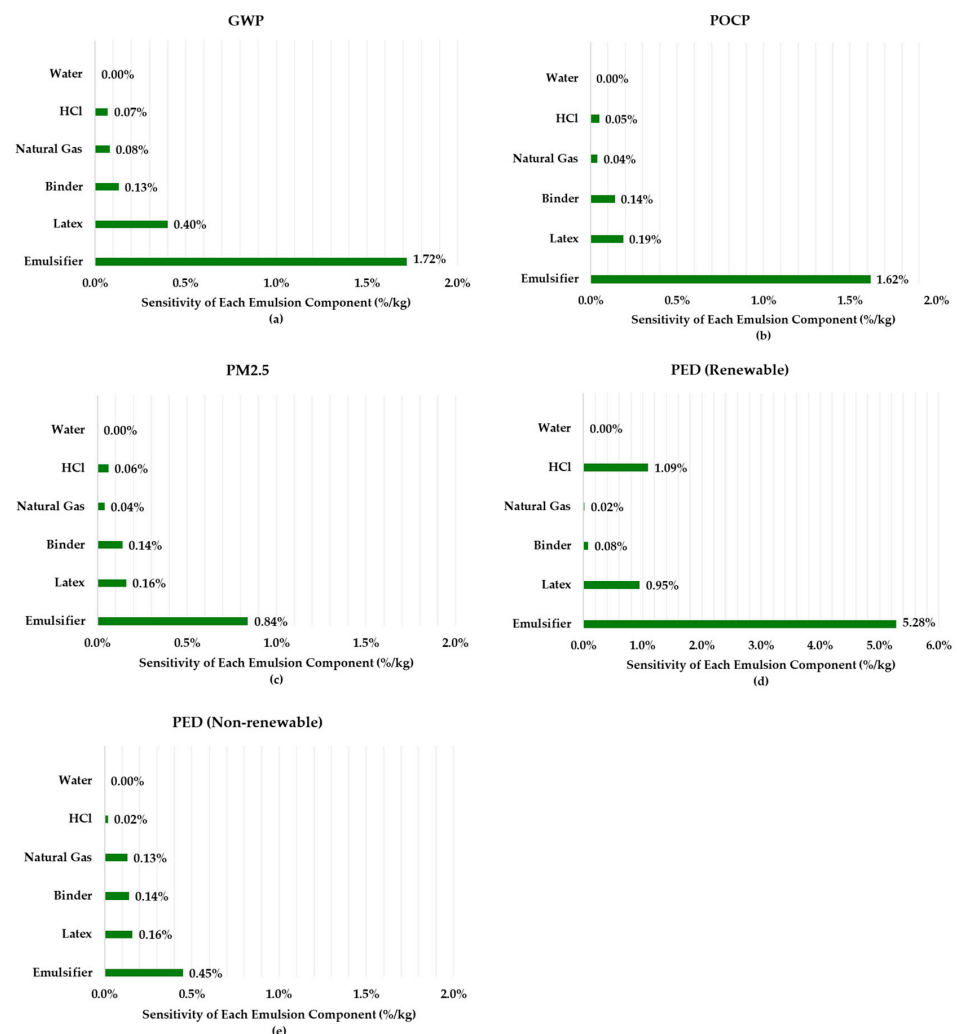


Figure 7. Sensitivity of (a) Global Warming Potential (GWP), (b) Photochemical Ozone Creation Potential (POCP), (c) Particulate Matter (PM_{2.5}), (d) Renewable Energy Demand, and (e) Nonrenewable Energy Demand per kilogram of each emulsified asphalt component. Panels (a–e) are presented together to facilitate comparison across impact categories while avoiding redundancy.

6. Discussion and Interpretation

Figure 8 displays the relative performance of each emulsified asphalt type across five environmental impact categories: PM_{2.5}, nonrenewable primary energy demand, POCP, renewable primary energy demand, and GWP. Number one is assigned to the emulsified asphalt type with lowest relative impact, while number four is assigned to the one with the highest.

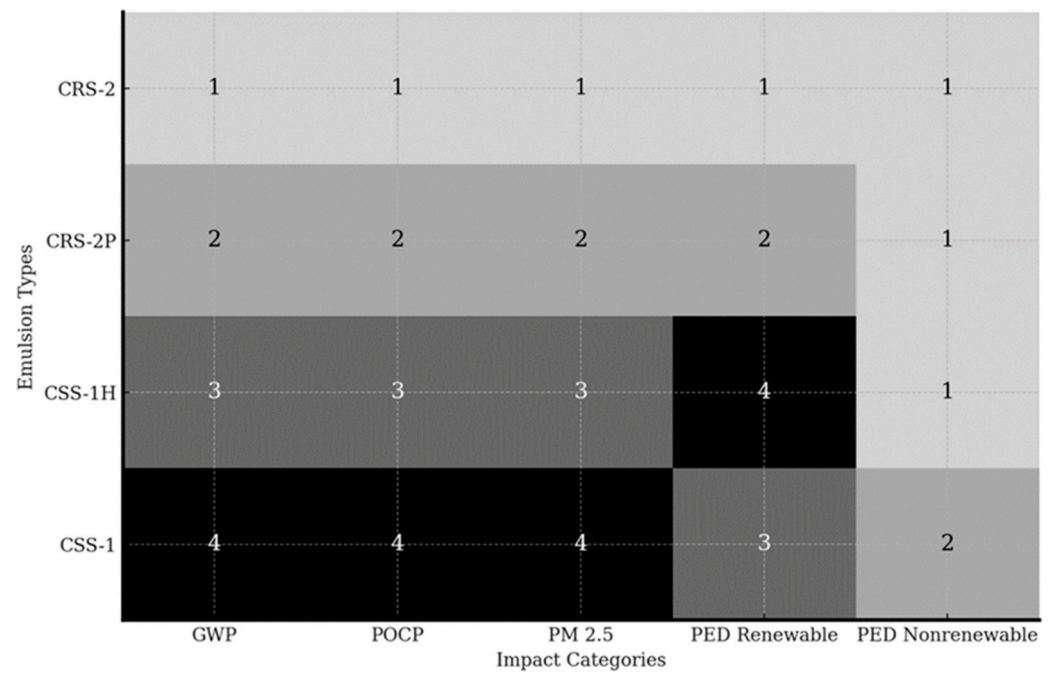


Figure 8. Impact assessment of selected emulsified asphalt types (1: least relative environmental impact; 4: highest relative environmental impact).

Figure 8 reveals a consistent pattern in relative environmental impact, with CRS 2 showing the lowest impact, followed by CRS 2P, CSS 1H, and CSS 1 as the highest. This same pattern is observed across the GWP, POCP, and PM 2.5 categories. The higher impacts observed for CSS-1 across these categories can be attributed to its slow-setting formulation, which requires higher emulsifying agent content and results in greater upstream energy use and emissions. The higher impacts observed for CSS 1 across these categories can be attributed to its slow-setting formulation, which requires the highest emulsifying agent content among the evaluated emulsions, resulting in greater upstream energy use and emissions.

In the nonrenewable primary energy demand category, CRS 2, CSS 1H, and CSS 1 exhibit identical energy use, suggesting that the asphalt binder and emulsifying agent in these formulations contribute similarly to nonrenewable energy consumption. In contrast, CRS 2P records the highest value in this category, primarily due to the inclusion of a specific additive in its formulation. This finding highlights the influence of polymer modification on fossil-based energy demand at the production stage.

In the category of renewable primary energy demand, a clear distinction emerges between emulsion types: slow-setting formulations exhibit nearly twice the impact of rapid-setting ones. Analysis of their composition shows that slow-setting emulsions contain a lower proportion of binder and a substantially higher amount of emulsifying agent. On average, the amount of emulsifying agent in slow-setting emulsified asphalt is nearly sevenfold greater than that used in rapid-setting types. This points to greater reliance on renewable energy in the upstream production of emulsifying agents. Furthermore, the

elevated impact of CSS 1H in this category can also be attributed to the use of additional ingredients such as latex. These results emphasize that renewable energy demand is particularly sensitive to chemical additive production, underscoring the importance of emulsifier and modifier selection from an environmental perspective.

When analyzing the relative proportion of individual components across different emulsified asphalt formulations, asphalt binder consistently stands out as the dominant input. However, its environmental influence declines from rapid-setting to slow-setting types. This shift is driven by the fact that slow-setting emulsions are formulated with less binder compared to their rapid-setting counterparts. Meanwhile, the roles of HCl and water remain negligible in terms of overall environmental contribution, regardless of emulsified asphalt type. Taken together, the interpretation confirms that environmental impacts at the production stage are governed by both material quantity and per-unit environmental intensity, with emulsifying agents and modifiers playing a disproportionately important role despite their lower mass fractions.

7. Conclusions

This study evaluated the relative environmental burden linked to emulsified asphalt production in the US, with particular emphasis on cationic variants. It adopted a cradle-to-gate system boundary and used one metric ton of emulsified asphalt as the reference quantity. Four widely used cationic emulsified asphalt types—CSS 1, CSS 1H, CRS 2, and CRS 2P—were selected based on their broad presence in transportation department specifications across all fifty states. Data was collected from seventeen emulsified asphalt production facilities, where comprehensive evaluations took place. The findings revealed that cationic emulsified asphalt with faster setting behavior, such as CRS 2 and CRS 2P, had a lower relative environmental burden compared to slower-setting types like CSS 1 and CSS 1H. The increased relative environmental impact observed in the slower-setting formulations was largely due to their greater reliance on emulsifying agents and additional chemical ingredients in comparison to the faster-setting alternatives.

Overall, the results clearly demonstrate that emulsified asphalt production is associated with distinct and formulation-dependent environmental impacts, particularly in terms of GWP, PM_{2.5}, POCP, and renewable and nonrenewable primary energy demand. These impacts are primarily governed by material composition, especially the quantity and type of emulsifying agents and chemical additives used in different formulations.

In addition, the analysis also identified transportation as a relatively minor contributor to GWP, ranging from 0.2 percent to 19.4 percent across all cases, with an overall average near 4.1 percent. Only three facilities showed transportation-related impacts that accounted for more than 10 percent of the total value. This finding reinforces that material production processes, rather than transportation, dominate the environmental footprint of emulsified asphalt within the cradle-to-gate system boundary.

The sensitivity analysis revealed a consistent proportional response between changes in input values and the corresponding environmental results. Asphalt binder proved to be the most influential material, responding most strongly to percentage changes. Emulsifying agent and latex followed, each contributing noticeably to the total environmental impact of emulsified asphalt production. Asphalt binder, which makes up a significant portion of the mixture, had the largest effect across all impact categories. On the other hand, when the analysis focused on sensitivity per kilogram of material rather than total content, the emulsifying agent emerged as the most dominant factor. These results further emphasize that environmental impacts are strongly influenced by both material quantity and per-unit environmental intensity, highlighting the importance of formulation choices in reducing production-stage environmental burdens.

In conclusion, this study aimed to deepen the understanding of the environmental impacts linked to emulsified asphalt production. By comparing multiple emulsified asphalt types, the analysis identified key stages within the product life cycle that contribute most significantly to overall environmental burden. Recognizing these critical points provides a foundation for developing focused strategies to improve sustainability across the emulsified asphalt industry.

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Abbreviations

The following abbreviations are used in this manuscript:

AASHTO	American Association of State Highway and Transportation Officials
ASTM	ASTM International (formerly American Society for Testing and Materials)
CMA	Cold Mix Asphalt
CRS	Cationic Rapid Setting
CSS	Cationic Slow Setting
DOT	Department of Transportation
eGRID	Emissions and Generation Resource Integrated Database
EPD	Environmental Product Declaration
GHG	Greenhouse Gas
GWP	Global Warming Potential
HCl	Hydrochloric Acid
HMA	Hot Mix Asphalt
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MJ	Megajoule

MS	Medium Setting
PED	Primary Energy Demand
PM _{2.5}	Particulate Matter with aerodynamic diameter $\leq 2.5 \mu\text{m}$
PCOP	Photochemical Ozone Creation Potential
QS	Quick Setting
RS	Rapid Setting
SDS	Safety Data Sheet
SS	Slow Setting
US	United States

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