Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 12, No. 01, January, 2026

Comparative Life Cycle Assessment of Carbon Fiber and Nano-Silica Modified Asphalt Mixtures

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Received 09 October 2025; Revised 16 December 2025; Accepted 21 December 2025; Published 01 January 2026

Abstract

In recent years, several studies have focused on enhancing the performance of asphalt mixtures using various additives; however, the environmental implications of these modifications have received limited attention. Accordingly, this study aims to evaluate the environmental impacts of asphalt mixtures incorporating carbon fiber (CF) and nano silica (NS) using the Life Cycle Assessment (LCA) methodology. In the current study, four mixtures were modelled and analyzed using SimaPro software: conventional asphalt mix (CAM), carbon fiber asphalt mix (CFAM), nano silica asphalt mix (NSAM), and carbon fiber–nano silica asphalt mix (CFNSAM). The assessment included the production cycle from raw material extraction to wearing surface installation, integrating laboratory performance data with the Ecoinvent v3.6 inventory. Results indicated that CAM exhibited the lowest environmental burden, whereas CFNSAM showed the highest impact resulting from the considerable energy inputs associated with carbon fiber fabrication. NSAM offered a balanced outcome, with moderate environmental impacts and satisfactory mechanical performance, positioning it as a more sustainable alternative. Overall, nano silica modification demonstrates promising potential for eco-efficient pavement applications.

Keywords: LCA; Carbon Fiber; Nano Silica; Modified Asphalt Mix; SimaPro; Ecoinvent.

1. Introduction

Flexible pavement asphalt mixtures typically consist of asphalt binder, mineral fillers, aggregates, and interconnected air voids [1], offering favorable mechanical properties, ease of construction, and cost-effectiveness [2]. However, increasing traffic loads and climate variability have accelerated the deterioration of asphalt pavements, leading to issues such as fatigue cracking in cold climates, rutting in hot conditions, and moisture-induced stripping [3]. To improve the durability of asphalt pavements, researchers have been exploring alternative materials that enhance the performance of asphalt mixtures [4]. Despite this, most studies focus solely on laboratory performance without considering environmental impacts.

However, the expansion of road infrastructure often leads to significant environmental issues that pose risks to both the environment and human health. The construction of roads requires various raw materials, including aggregates, bitumen, and chemical additives, which involve considerable consumption of natural resources and energy throughout extraction, manufacturing, and processing phases. As a result, road construction contributes to energy consumption, emissions of dust and gases, land degradation, depletion of non-renewable resources, noise pollution, and the generation of solid waste [5].

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https://doi.org/10.28991/CEJ-2026-012-01-022

The primary objective of this research is to assess the environmental burdens associated with asphalt mixes modified with carbon fiber and/or nano silica using a life-cycle approach. The goal is to develop reliable and sustainable alternatives for asphalt pavements that can be practically implemented. The results of this study are primarily intended to assist decision makers in the industry, providing a valuable tool for developing strategies and policies related to the construction of asphalt pavement.

Life Cycle Assessment (LCA) is widely recognized as a well-established and internationally accepted methodology for quantifying and comparing the environmental impacts of processes, enabling sustainability evaluation [6, 7]. It includes the assessment of all resource consumption and pollutant emissions throughout the life cycle of a process, covering stages such as raw material extraction and processing, chemical manufacturing, and transportation, as well as final disposal and recycling [8, 9]. Currently, the LCA method is well-developed, with an impact assessment phase that gathers and quantifies all environmental impacts.

Although significant progress has been made, most previous LCAs have primarily focused on conventional asphalt mixtures or those modified with a single additive. There has been limited research on dual-modified systems. Furthermore, few studies have incorporated laboratory-based performance data into life-cycle assessments, making it difficult to link environmental impacts with mechanical advantages and cost implications. Thus, the present study seeks to conduct an integrated environmental assessment of asphalt mixtures modified with carbon fiber and/or nano silica, after applying the proper laboratory tests, by applying the LCA tool. The evaluation follows the LCA steps: goal of study (consisting of system boundaries, functional unit, assumptions, and limitations), life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The analysis is carried out using SimaPro software 9.6 in association with the Ecoinvent database version 3.6.

1.1. Literature Review

Many studies have examined the environmental impacts of asphalt mixtures, and several have explored asphalt mastics modified with different additives [10-12]. These efforts aim to reduce environmental pressures and support sustainable development by incorporating eco-friendly materials into pavement infrastructure [13, 14]. However, the existing literature does not report a comprehensive LCA of asphalt mixtures modified with carbon fiber and/or nano silica, which represents an innovative mixture previously proposed. In this study, findings from various international LCA-based pavement construction assessments are reviewed, and the key characteristics of asphalt mixtures examined in past research are presented in Table 1.

Table 1. Summary of the main characteristics of previous life cycle assessment studies on asphalt mixtures

Study reference	Function unit	LCA method	Software	Data source
Sackey et al. [15]	1 ton of nano silica modified mixtures	TRACI	Open LCA	Databases, Ecoinvent v.2.2
Suwarto et al. [16]	1-km road section, 3.5 m wide and 40 mm thick	ReCiPe 2016 Midpoint (H)	SimaPro 9.3.3	Databases, Ecoinvent v.3.8
Martinez-Soto et al. [17]	1 km pavement section	ReCiPe (H) 2016	SimaPro	Databases, Ecoinvent v3
Gupta et al. [18]	1 m² porous asphalt	LCA indicators + MCDA	SimaPro	No explicit LCI database (e.g., Ecoinvent or similar) is cited for LCA modeling in the published article
Xie [19]	1 km of pavement over the full life cycle	IPCC method	Open LCA	Data sourced from the GIS-LCA data platform
Raha et al. [20]	1 kg CFRP component	ReCiPe 2016, CED	-	Literature sources, European average metrics, and standardized environmental emission factors
Khater et al. [21]	The wearing surface layer of a pavement section measuring 1 km in length and 1 m in width	CML2001	SimaPro	Databases, Ecoinvent v3
Yue et al. [22]	The wearing surface layer of a pavement section measuring 1 km in length and 1 m in width	CML2001	SimaPro	Databases, Ecoinvent v3

Sackey et al. [15] assessed the environmental impacts of nano silica–modified mixtures by focusing on emissions associated with material production within a life cycle assessment framework. Their findings indicated that incorporating nano silica resulted in negligible adverse effects on the overall environmental profile, with changes in all impact categories remaining at or below 1%.

Suwarto et al. [16] employed LCA to examine the impact of using nano silica on surface course mixtures. Results observed that in the asphalt mixing stage, both electricity and heat were almost equally responsible for the environmental impacts, emphasizing the need to manage energy consumption in that phase.

Martínez et al. [17] found that synthetic fibers like aramid and polyester generate the highest environmental impacts in asphalt mixes due to their energy-intensive petrochemical production. Fiberglass shows moderate impacts linked to high-temperature processing, while cellulose fibers have the lowest footprint, benefiting from their natural origin and simpler manufacturing.

Gupta et al. [18] evaluated the environmental performance of different additives used in porous asphalt as part of a multi-criteria decision-making framework. Their assessment compared resource use and emissions linked to each additive. The findings suggest that additives with energy-intensive manufacturing processes, including aramid fiber, cellulose fibers, aramid pulp, and aramid–polyolefin fibers, show poorer environmental performance due to their energy-intensive manufacturing and higher associated emissions.

Xie [19] conducts a cradle-to-grave assessment of polyester-fiber-reinforced asphalt. The study shows that polyester fiber production is the main source of environmental burden, driven by energy-intensive petrochemical processes. While the fibers enhance mixture durability, their upstream manufacturing impacts outweigh those from transportation, mixing, and end-of-life stages.

Stoiber et al. [20] conducted LCA of carbon-fiber-reinforced polymer (CFRP); it was found that its production, particularly carbon fiber and epoxy resin, has a much higher environmental impact compared to steel reinforcement, especially in global warming potential and resource depletion. Despite CFRP’s mechanical advantages, its environmental burden remains higher at the material production stage. Khater et al. [21] performed a comparative LCA of asphalt mixtures incorporating composite admixtures of lignin and glass fibers. Their findings showed that bitumen production was the dominant contributor across most environmental impact categories. In addition, asphalt mixture manufacturing contributed most significantly to the OLD impact category, while glass fiber production exhibited the highest contribution to the HTP category.

Yue et al. [22] assessed the environmental impacts of four types of asphalt mixtures, Control Asphalt Mix (CAM), Diatomite-Modified Asphalt Mix (DMAM), Lignin Fiber–Modified Asphalt Mix (LFMAM), and a Diatomite–Lignin Fiber composite mix (DLFMAM), using a life cycle assessment approach. The study found that DMAM and CAM had the lowest environmental impacts across most categories, with DMAM closely resembling the control mix. LFMAM had the highest impact, followed by DLFMAM, although both had only slight increases in most categories when excluding human toxicity. Overall, DMAM, LFMAM, and DLFMAM are considered viable alternatives to conventional asphalt with minimal environmental impact.

2. Objective and Methodology

LCA provides a theoretical framework for assessing the environmental impacts of pavement systems across all stages, from raw material extraction and manufacturing to transportation, service life, and end-of-life processes, including recycling or disposal.

Over the last several decades, ISO developed LCA methodologies and published the ISO 14040 and ISO 14044 standards [23, 24]. These documents provide a standardized framework for defining the goal of the study, applying inventory analysis, performing impact evaluation, and interpreting the outcomes, as introduced in Figure 1. Such standards have also facilitated the development of numerous analytical frameworks and computational tools to assess environmental impacts across pavement LCA [21, 25, 26].

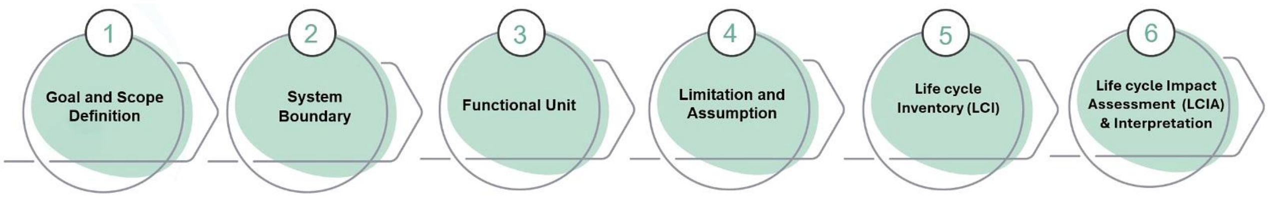


Figure 1. Framework Flowchart

In this study, the life cycle assessment was conducted in accordance with ISO 14040 and ISO 14044 standards, adopting a cradle-to-grave approach to evaluate asphalt mixtures and encompassing four main stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. Before conducting the LCA, a series of laboratory experiments was implemented to evaluate the technical efficiency of asphalt mixtures altered with different ratios of carbon fiber (CF) at 0.1%-0.5% of mixture weight and nano silica (NS) at 2%-10% of bitumen weight. Experimental results showed that 0.30% carbon fiber (by total mixture weight) and 8% nano silica (by bitumen weight) have the best impact on the mechanical and durability properties of the asphalt mixture. These tests followed standard AASHTO procedures and provided key mechanical indicators for input into the LCA model. The combined CF–NS admixture demonstrated superior performance compared with single-modifier and control mixtures, particularly in terms of strength retention and resistance to moisture and thermal damage.

Table 2 presents the main results of Marshall Immersion, Indirect Tensile Strength (ITS), and Wheel Tracking tests for four asphalt mixture variants: conventional asphalt mixture (CAM), carbon-fiber-modified asphalt mixture (CFAM), nano silica-modified asphalt mixture (NSAM), and composite carbon fiber–nano silica asphalt mixture (CFNSAM). These results represent original experimental data generated in this study under controlled laboratory conditions.

Table 2. Laboratory test results of various asphalt mixtures

Test	Marshall Immersion*			Indirect Tensile Strength **		Wheel Loading Tracking
Designation No.	AASHTO T165-74			AASHTO T-283		AASHTO T324-14
Asphalt Mix	MS1 [kg]	MS2 [kg]	RSI [%]	ITS1 [MPa]	ITS2 [MPa]	Rutting depth [mm]
CAM	1803	1701	94.3	2.8	2.582	1.73
CFAM	2106	2050	97.3	3.7	3.539	1.03
NSAM	2675	2450	91.6	3.020	2.822	0.97
CFNSAM	2197	2107	96	4.275	4.194	0.73

* MS1 is the Marshall Stability after 30 minutes of water immersion at 60 °C, MS2 after 24 h of immersion at 60 °C, and RSI is the Retained Strength Index.

** ITS1 is the Indirect Tensile Strength after 24 h at 25 °C [dry], and ITS2 is the strength after 2 hours conditioning at −15 °C with 70–80% saturation.

The results confirm that the CFNSAM mixture exhibited the highest moisture resistance and cracking resistance, outperforming single-modifier and control mixes. These findings provide the empirical foundation for the subsequent LCA, linking environmental indicators with laboratory-derived mechanical performance.

2.1. Goal and Scope Definition

2.1.1. Goal of the Study

The primary objective of this study is to evaluate and compare, using an LCA approach, the environmental burdens of asphalt mixtures modified with carbon fiber and/or nano silica selected for use in the wearing surface layer of flexible pavements. In addition, the environmental performance of these mixtures is compared with that of a CAM to better understand the contribution of the selected additives and to support informed decision-making.

2.1.2. System Framework and Boundaries

System boundaries and inventory parameters are critical elements that strongly influence the scope, results, and interpretation of an environmental assessment. Accordingly, this study focuses on comparing the environmental burdens related to the manufacturing stages of the investigated asphalt mixtures.

Pavement construction life cycles encompass various stages, including pavement design, raw materials production, bituminous mixtures manufacturing, transportation, pavement construction, usage, maintenance, and end of life processes. Environmental contributions from design phases, involving blueprint production and personnel travel, represent minimal impacts relative to subsequent stages [27, 28]. Base and subbase layer construction phases remain outside the assessment scope, given the premise that these structural elements experience identical construction procedures and operational longevity regardless of modifier presence [29]. Significantly, materials extraction and asphalt mixture manufacturing constitute the dominant environmental burden sources when contrasted with pavement construction and demolition stages [30]. Pavement construction operations encompass site preparation and ground levelling, foundation densification, subbase and base layer installation, asphalt mixture application, grading, and compaction procedures. Given that environmental burden variations among modified asphalt mixture types exclusively occur during wearing surface installation, this analysis focuses solely on wearing surface layer construction. Usage, maintenance, and end of life stages remain beyond the assessment boundaries due to their disproportionately substantial environmental consequences relative to remaining phases [31-34].

Based on these considerations, a cradle-to-gate system boundary is adopted in this study, encompassing raw material extraction and production, asphalt mixture manufacturing, transportation, and the construction of the wearing surface layer, as illustrated in Figure 2.

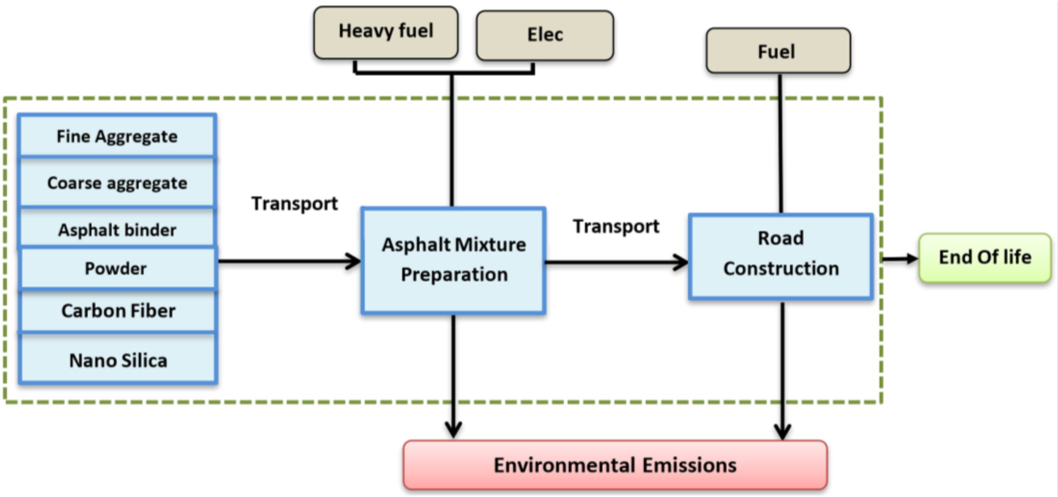


Figure 2. Life Cycle Assessment system boundaries

2.1.3. Functional Unit

Geometric specifications, performance criteria, and operational lifespan considerations define the functional unit for the road pavement LCA. In the present study, the primary inventory data were collected from field investigations conducted during construction on Egypt's Cairo-Suez Desert Road, which spans approximately 106 Km. The road features 3.76-meter lane widths, with six traffic lanes and three heavy transport lanes leading to the regional ring road junction. Pavement design calculations were based on traffic parameters and Egyptian subgrade soil characteristics, in accordance with AASHTO design methodology. Traffic specifications for the road include an average annual daily traffic of 20,000 vehicles/day, with 10% heavy vehicles, and a California Bearing Ratio (CBR) value of 11%. The pavement is assumed to have a 15-year service life.

The reference unit is defined as the pavement wearing surface layer corresponding to a standard highway section with a 1 km length and a 1 m width. This functional unit is illustrated in Figure 3, which presents the pavement cross-section. The analysis is limited to the asphalt wearing course, with all emissions, material inputs, environmental impacts, and energy consumption quantified based on this functional unit.

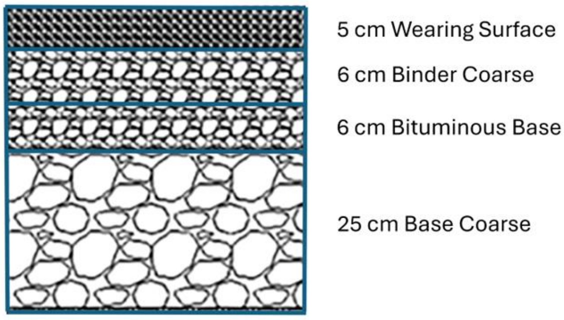


Figure 3. Typical highway cross-section

2.1.4. Study Assumptions and Limitations

The execution of LCA studies is based on data accessibility and selected methodological approaches. Essential considerations encompass evaluating data accessibility, temporal requirements for study completion, and necessary financial investments, all while maintaining alignment between result quality and established project goals. The present investigation operated within specific, defined parameters:

- Material scope encompassed limestone aggregates, filler, and bitumen for traditional asphalt mix formulations, while modified mixtures incorporated carbon fibers and nano silica as additional components.
- Environmental impact calculations for raw material extraction, manufacturing operations, diesel fuel production chains, and electrical energy generation processes reflected Egyptian operational conditions.
- Loading operations for raw materials through transportation were excluded from the impact assessment.
- Transportation-related environmental impacts are considered solely for unidirectional material movement from materials providers to the asphalt plant and subsequently from production facilities to construction locations, omitting return journeys of unloaded vehicles.

2.2. Life Cycle Inventory (LCI)

Life cycle inventory encompasses resource utilization, energy requirements, and environmental releases to aquatic, terrestrial, and atmospheric systems throughout each stage of pavement life cycle processes. This section provides a detailed characterization of the input parameters for LCI development, facilitating the design of system components across multiple alternatives. Inventory data came from scholarly publications, established databases, and laboratory investigations. The LCA study used two data categories. Primary data represented production-specific information from manufacturers, process operators, service providers, and industry associations. Secondary data included standardized or averaged values for the analysed solutions, accounting for associated products and operational activities. Vidal et al. [35] and Vandewalle et al. [36] provided secondary data sources, along with adapted primary data, national repositories, and consulting resources.

This section outlines design specifications and material mass balance calculations for asphalt mixture manufacturing processes. Ecoinvent database version 3.6 supplied LCI information. This covered resource extraction, material manufacturing, energy consumption, and transportation requirements for asphalt mixture production operations. Environmental impact assessment and burden analysis across all alternatives utilized SimaPro software V9.6 for computational evaluation.

2.2.1. Data sourcing of Raw Materials

Modelling of natural aggregates for asphalt mixture production utilized limestone materials, with corresponding LCI data for extraction operations sourced from the Ecoinvent database unit process designated as "Limestone, crushed, for mill {RoW}| market for limestone, crushed, for mill | Cut-off, S". Bitumen production LCI information was retrieved from the Ecoinvent database entry "Bitumen, at refinery/kg/US". Due to the unavailability of carbon fiber and nano silica production datasets within the Ecoinvent database, the corresponding inventory data were sourced from previously published studies. These data were verified and aligned with actual manufacturing processes to ensure their reliability and compatibility with the LCA framework.

As shown in Figure 4, the manufacturing process of polyacrylonitrile [PAN] carbon fiber comprises five principal stages: PAN polymerization, oxidation, carbonization, surface treatment, and sizing. The raw material acrylonitrile [AN] was sourced from the Ecoinvent database using the unit process "Acrylonitrile {GLO} | market for acrylonitrile | Cut-off, S". PAN precursor fiber is typically produced by polymerizing AN in the presence of a solvent—such as sodium thiocyanate, nitric acid, dimethylacetamide, or dimethylformamide—followed by either wet spinning or air-gap spinning processes, which include fiber stretching and washing steps. Dimethylacetamide solvent was selected from the Ecoinvent database unit process "Dimethylacetamide {GLO}| market for dimethylacetamide | Cut-off, S" [37-43].

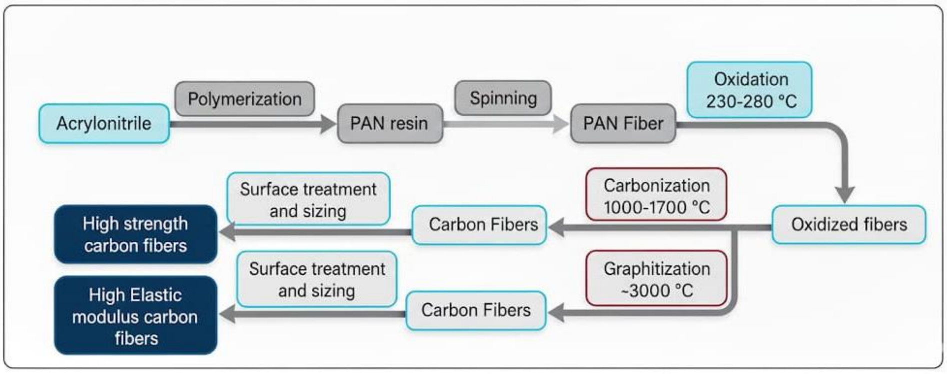


Figure 4. Production processes manufacture Polyacrylonitrile (PAN) CF [37-43]

Primary data regarding carbon fiber inventory were obtained from published scientific sources, encompassing raw material quantities and energy requirements as documented in Table 3. The processes of nano silica manufacturing are not found in the Ecoinvent database; therefore, data were sourced from the literature. The inventory data for the nano silica were collected as primary data, including the amount of raw materials and energy, as shown in Table 4.

Table 3. Studies from the literature on the carbon fiber manufacturing phase inventory

Reference	Ecoinvent flow [Input]	Amount/ kg of carbon fibers
Das [44]	Acrylonitrile [kg]	2.09
	Vinyl-acetate [kg]	0.018
	Heat, district or industrial, natural gas [MJ]	529
	Electricity, medium voltage [kWh]	21.92
Duflou et al. [45]	Acrylonitrile [kg]	1.88
	Nitrogen liquid [kg]	11.52
	Heat, district, or industrial, natural gas [MJ]	191.47
	Electricity, medium voltage [kWh]	44.87
	Steam in the chemical industry [kg]	33.87
Jacquet et al. [46]	Acrylonitrile [kg]	2
	Vinyl-acetate [kg]	0.02
	Nitrogen liquid [kg]	11.5
	Heat, district or industrial, natural gas [MJ]	360.2
	Electricity, medium voltage [kWh]	33.4
	Steam in the chemical industry [kg]	33.9
Nunes et al. [47]	Polyacrylonitrile [kg]	1.82
	Energy [MJ]	286
Created model	Acrylonitrile [kg]	2
	Dimethylacetamide [kg]	0.02
	Electricity, medium voltage [kWh]	21.92
	Heat, district, or industrial, natural gas [MJ]	200

Table 4. Studies from the literature on the nano silica manufacturing phase inventory

Reference	Ecoinvent flow [Input]	Amount/ kg of Nano silica
Sackey et al. [15] and Roes et al. [48]	Sodium silicate	3.9 kg
	Sulfuric acid	0.66 kg
	Heat [Natural gas]	15–24 MJ
	Water	40 kg
Gu et al. [49]	Sodium bicarbonate	0.41 kg
	Sulfuric acid	0.445 kg
	Quartz Sand	0.76 kg
European Commission [50]	Silicon tetrachloride	2.83 kg
	Hydrogen	0.067 kg
	Natural gas	15–18 MJ
Created model	Sodium bicarbonate	0.41 kg
	Sulfuric acid	0.445 kg
	Quartz Sand	0.76 kg
	Natural gas	15MJ

2.2.2. Asphalt Mixture Manufacturing Process

The present phase evaluates environmental consequences arising from manufacturing different asphalt mixture formulations analysed within this investigation. Energy requirements for asphalt mixture production predominantly involve heavy fuel oil and electrical power consumption. Thermal processes requiring fuel include asphalt heating and aggregate drying operations, whereas electrical energy drives construction equipment. Manufacturing operations generate significant

particulate matter through aggregate drying and heating procedures, while fossil fuel combustion produces CO_2 emissions. Moreover, thermal treatment of asphalt during mixing operations results in the release of multiple hazardous gaseous compounds. This analytical phase focuses on quantifying environmental impacts associated with producing the diverse asphalt mixture types under investigation.

LCI data related to electricity generation in Egypt were created from the Ecoinvent database using the process "Electricity, medium voltage, aluminium industry {CN} | electricity voltage transformation from high to medium voltage, aluminium industry | APOS, S". In addition, heavy fuel oil production was modeled based on the Ecoinvent process "Heavy fuel oil {ROW} | heavy fuel oil production, petroleum refinery operation | APOS, S". However, the specific electricity and heavy fuel oil consumption required to produce one ton of asphalt mixture were obtained directly from the General Nile Company plant, as summarized in Table 5.

Table 5. Main parameters of the asphalt mixing plant

Equipment	Power [kW]	Rated Capacity [t\h]	Mixer capacity [kg]	Fuel Consumption [kg\t]	Fuel type	Emission Concentration [mg\Nm^3]
SAP 100	232	100	1300	$\leq$ 6.5	Heavy oil	$\leq$20

2.2.3. Transportation Process

Environmental impact assessment encompassed the effects of materials transportation resulting from emissions generated through fuel combustion during transit between raw material extraction locations and the asphalt mixing facility, as well as from production facilities to construction sites. Life cycle inventory (LCI) data for material transport operations were determined primarily by vehicle specifications and actual travel distances from the ongoing project in Egypt. Calculations for fuel consumption and transportation emissions incorporated material mass, vehicle classifications, transport distances, and road infrastructure categories. Heavy-duty vehicles (HDV) were designated as the standard transport mode for all materials and mixtures. Environmental impact evaluation for raw material and asphalt mixture highway transportation employed the Ecoinvent database process "Transport, freight, lorry > 32 metric ton, EURO3 {ROW}| transport, freight, lorry > 32 metric ton, EURO3 | APOS, S". Transport distances applicable to all materials and asphalt mixtures examined in this study are presented in Table 6.

Table 6. Transportation process and distance

Material	From	To	One-way transport distance [km]
Limestone "Coarse aggregate- fine aggregate- filler"	Extraction site	Asphalt mixing plant	160
Bitumen	Petrol refinery		90
Carbon fibers	Manufacturing site		90
Nano silica			95
Asphalt mixture	Asphalt mixing plant	Construction site	60

2.2.4. Wearing Surface Construction Process

Environmental impacts during this phase stem from emissions produced through combustion processes in construction equipment utilized for asphalt pavement layer distribution and compaction operations. Table 7 presents life cycle inventory (LCI) data for construction machinery, specifically finishers and heavy vibratory rollers.

Table 7. Equipment energy usage

Equipment	Fuel type	Consumed energy [L/1000m^2]
Finisher	Diesel	40
Heavy vibratory roller	Diesel	20

Energy requirements for pavement construction predominantly derive from diesel fuel consumption by construction equipment. The diesel fuel was modeled using the Ecoinvent database entry "Diesel {ROW}| diesel production, petroleum refinery operation | APOS, S". Paving procedures were considered uniform across all asphalt mixture types examined.

2.2.5. Mass Balance for Various Scenarios

Calculations for mass balances across various asphalt mixture scenarios utilized experimental test results and multiple data sources, employing a custom Excel spreadsheet model incorporating density values and mix design parameters derived from experimental testing for each scenario formulation. Assessment of energy requirements and material mass balances encompassed four asphalt mixture types: conventional asphalt mix (CAM), carbon fiber modified asphalt mix (CFAM), nano silica modified asphalt mix (NSAM), and carbon fiber-nano silica modified asphalt mix (CFNSAM), examined in this investigation, with results documented in Table 8.

Table 8. Mass balance and consumed energy of different asphalt mixes

Balance	Component	CAM	CFAM	NSAM	CFNSAM
Weight [ton]	Coarse aggregate	57.09	56.09	57.1	56.7
	Fine aggregate	50.37	49.49	50.39	50.04
	Filler	4.48	4.4	4.48	4.45
	Bitumen	6.51	6.42	6.55	6.52
	Carbon fibers	-	0.35	-	0.36
	Nano silica	-	-	0.52	0.52
	Asphalt mixes	118.45	116.75	119.05	118.6
Energy consumption in asphalt mix manufacturing	Heavy fuel oil [kg]	769.9	758.9	773.8	770.9
	Electricity [kWh]	274.8	270.86	276.2	275.15
Energy consumption in the wearing surface construction	Diesel fuel [kg]	51	51	51	51

3. Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment (LCIA) phase seeks to identify and quantify the magnitude and significance of potential environmental impacts associated with a product or process throughout its life cycle.

3.1. Selection of LCIA methodology and impact categories

The analytical framework uses the problem-oriented methodology to reduce uncertainties in outcomes. This follows LCA methodological guidelines CML2001 method. The goal differentiates potential environmental impacts among assessed scenarios while identifying alternatives with minimal environmental footprints. The CML2001 approach offers advantages for this investigation through global applicability and consistency with established research objectives and geographical scope.

This methodology delivers a structured evaluation framework for environmental impact assessment using predetermined characterization factors. Impact categories chosen for this investigation form the fundamental framework within the LCA methodology based on CML 2001. These classifications characterize environmental consequences from pavement processes and derive from established methodological standards.

3.2. Classification

During classification procedures, inventory outcomes "elementary flows encompassing resource utilization, land occupation, and various chemical emissions" are assigned and integrated into designated impact categories through qualitative assessment methods.

3.3. Characterization

Characterization represents a fundamental component within the LCIA phase of LCA methodology. This process transforms inventory data "measured emissions or resource consumption" into standardized impact scores across designated environmental categories. Characterization factors serve as conversion coefficients, establishing the potential environmental consequences for individual substances. Category indicator calculations involve multiplying respective category intensities by corresponding characterization factors. Mathematical representation of characterization procedures in LCA follows established formulations [15, 21, 22, 51], as displayed in Equation 1.

$$IR_C = \sum_S CF_{cs} \cdot m_S \quad (1)$$

where, IRC represents the characterization indicator score for impact category C, CFCS denotes the characterization factor linking intervention S to impact category C, and ms refers to the magnitude of intervention S.

3.4. Normalization

Normalized scores were derived for each impact category to facilitate a comparative assessment of their relative importance. Normalization involves calculating ratios between impact scores for specific categories and baseline impacts from established references "designated as normalization factors". Computational procedures employed Equation 2 for these calculations [15]:

$$Nc = IR_C / R_C \quad (2)$$

where, Nc is the normalization score of impact category C, IRC is the characterization indicator score of category C, and Rc is the normalization factor of impact category C.

Although the normalization factors applied in this study are based on the 1995 global reference data [52], this dataset remains one of the most widely used benchmarks in SimaPro and Ecoinvent-based LCA studies, particularly for comparative analyses [22]. The 1995 normalization framework provides internal consistency with the characterization models adopted in this research and ensures comparability with earlier asphalt LCA literature. Nevertheless, more recent normalization sets have been developed; for example, the ReCiPe 2016 method provides updated global normalization factors [53], and the European Commission's Environmental Footprint 3.1 method offers further refined normalization/characterization factors [54]. The relative ranking of environmental impacts across impact categories is not expected to change significantly when applying these newer datasets [55]. Nevertheless, we acknowledge the limitation of adopting older reference data and recommend that future work adopt updated normalization datasets for improved accuracy. The normalized values used are listed in Table 9.

Table 9. The normalization values [22]

Impact category	Normalization factor [Rc]	Reference Unit
Global Warming Potential [GWP]	4.15E +13	kg CO2 eq/year
Eutrophication Potential [EP]	1.32E +11	kg PO4 eq/year
Acidification Potential [AP]	3.35E +11	kg SO2 eq/year
Abiotic Depletion Potential [ADP]	1.57 E +11	kg Sb eq/year
Human Toxicity Potential [HTP]	5.67E +13	kg p-DCB/year
Ozone Layer Depletion [OLD]	6.01E +8	kg CFC-11 eq/year
Freshwater Aquatic Ecotoxicity Potential [FWETP]	1.81E +12	kg p-DCB/year
Marine Aquatic Ecotoxicity Potential [METP]	1.9E +12	kg p-DCB/year
Terrestrial Ecotoxicity Potential [TETP]	1.4E +11	kg p-DCB/year
Photochemical Oxidant Formation Potential [POFP]	9.59E +10	kg C2H4 eq/year

3.5. Weighting and Grouping

Converting LCA outcomes into a single weighted score allows easier comparison of environmental impacts across products and scenarios. This simplifies decision-making by showing clearly whether an option performs better, worse, or equal to others, while also improving communication compared to reporting 3–18 separate indicators [56]. To derive such weights, this study applied a four-step panel approach integrated with Multi-Criteria Decision Aid (MCDA). Instead of directly ranking impact categories, the method embedded panellists' value judgments into the MCDA framework. Canadian participants assessed seven environmental principles: resource use, scale, ecosystem and human health, distance to target, reversibility, and duration, leading to weight factors for ten impact groups; as presented in Table 10. These were synthesized through MCDA into consolidated scores [57].

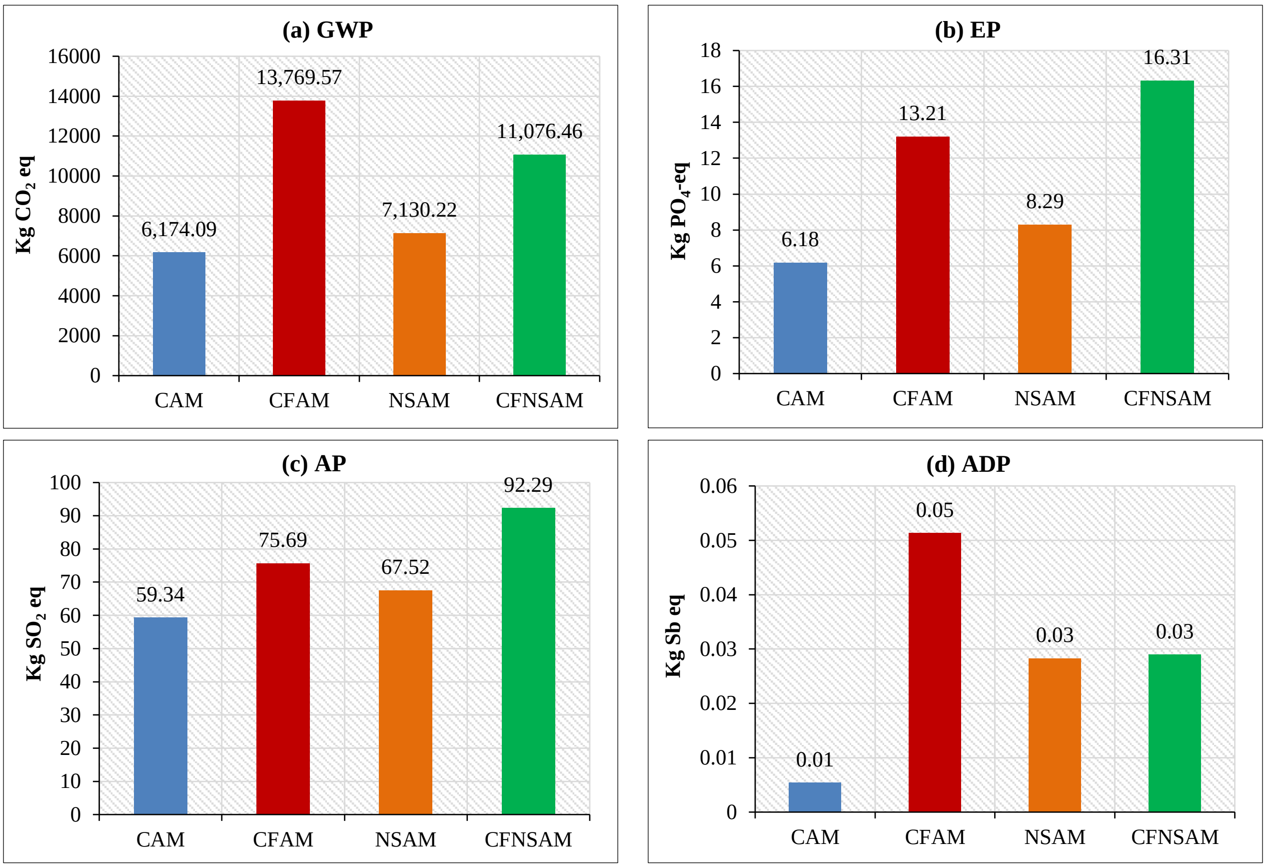
Table 10. Weighting factors of the Canadian citizens' panel [22]

Impact category	Weight %
[GWP]	18.2
[EP]	7.9
[AP]	9.2
[ADP]	12.9
[HTP]	8.5
[OLD]	13.1
[FWETP]	6.6
[METP]	6.6
[TETP]	6.6
[POFP]	6.8

4. Results and Discussion

4.1. Comparison of the LCA Characterization Values

The characterization outcomes for all impact categories across the different asphalt mixtures are illustrated in Figure 5 and summarized in Table 11. As shown in Figure 5-a, nano silica increased the GWP of 15.5% relative to the control asphalt mixture, whereas CF and composite mixtures exhibited significantly higher increases of 123% and 79.4%, respectively. Figure 5-b demonstrates that the EP of the asphalt mixtures NS, CF, and composite mixtures increased by 34.2%, 113.6%, and 164%, respectively, in comparison with the control asphalt mixture. The compound-modified mixture exhibits the poorest performance, as it records the highest eutrophication potential (EP) value.



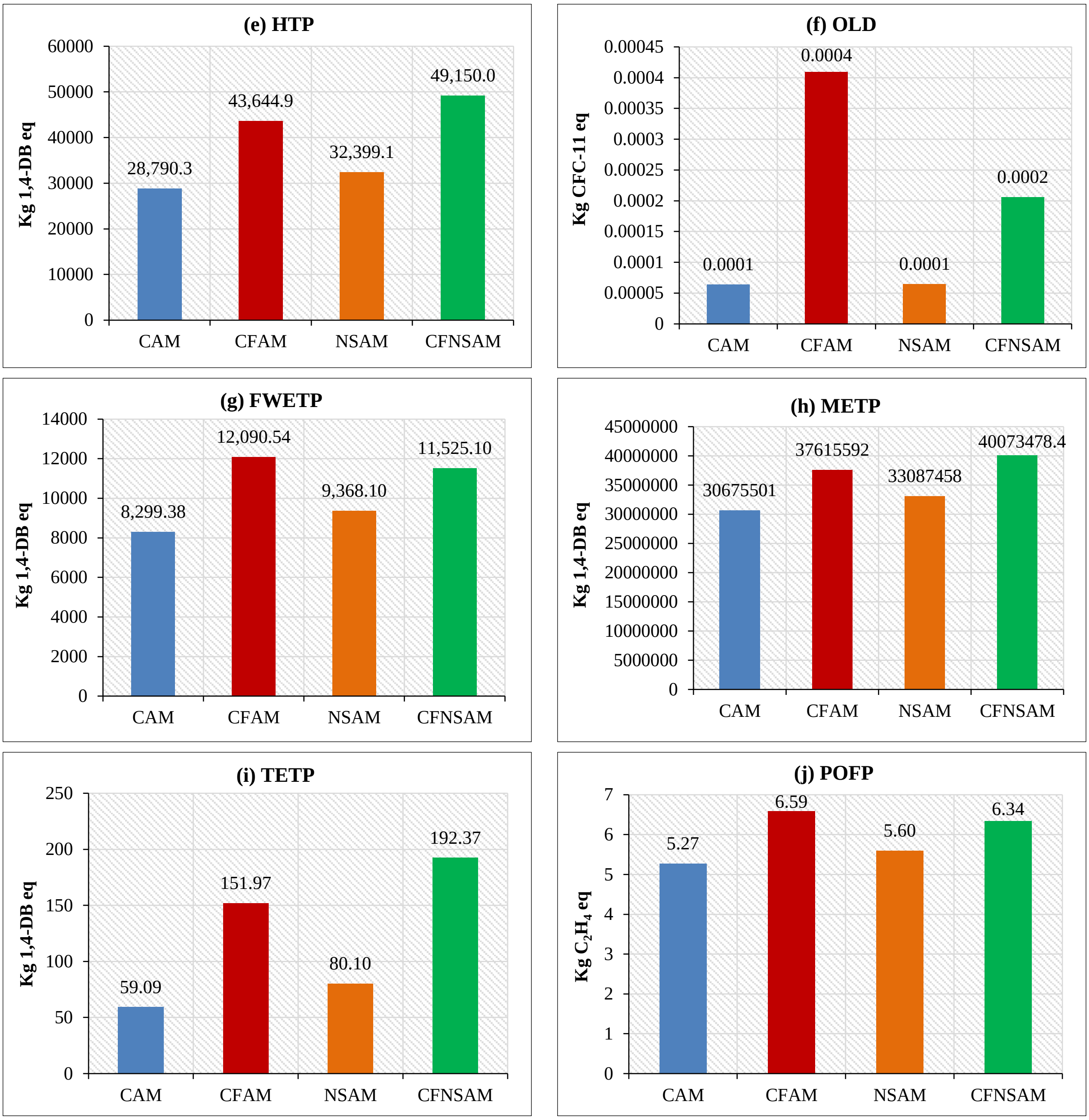


Figure 5. Characterization results of the compared mixtures

Table 11. LCIA results for different asphalt mixtures per functional unit

Impact category	Reference unit	Impact results			
		CAM	CFAM	NSAM	CFNSAM
GWP	[Kg CO2 eq]	6174.0911	13769.569	7133.2206	16270.2
EP	[Kg PO4-eq]	6.177900274	13.209577	8.287798785	16.31490755
AP	[Kg SO2 eq]	59.33748	75.688412	67.49175665	82.69802419
ADP	[Kg Sb eq]	0.005394595	0.051327914	0.028299547	0.028946862
HTP	[Kg 1,4-DB eq]	28790.27604	43644.946	32399.13712	49150.01283
OLD	[Kg CFC-11 eq]	6.38489E-05	0.000409594	6.45157E-05	0.000205874
FWETP	[Kg 1,4-DB eq]	8299.3778	12090.543	9368.1027	11525.09596
METP	[Kg 1,4-DB eq]	30675501	37615592	33087458	40073478.4
TETP	[Kg 1,4-DB eq]	59.088803	151.97254	80.098513	192.3734815
POFP	[Kg C2H4 eq]	5.267568858	6.58512887	5.597779982	6.342766299

Figure 5-c shows that the AP value was increased by adding nano silica and carbon fiber in the asphalt mixture compared to CAM by 13.8% and 27.5%, respectively. Additionally, the compound mixture increased the AP value by 39.37%. Furthermore, Figure 5-d shows that the ADP result of the mixtures of NSAM, CFAM, and CFNSAM increased by 424%, 851%, and 436%, respectively, with respect to the CAM; moreover, the carbon fiber demonstrates the worst negative environmental impacts.

In Figure 5-e, it's observed that HTP of carbon fiber and composite mixture showed a substantial increase of 51.59%, and 70.7%, respectively, compared to CAM. While nano silica exhibited a minor increase of 12.5%. The composite mixture showed the worst environmental impact. As shown in Figure 5-f, nano silica resulted in a slight increase in the OLD of 1 % relative to CAM, whereas CFNSAM exhibited significantly higher increases of 222.8%. The carbon fiber showed the worst OLD with an increase of 542% compared with CAM.

Figure 5-g demonstrates that NSAM showed an increase of 12.8% in FWETP compared to CAM, while CFAM and CFNSAM demonstrate more pronounced increases of 45.7% and 38.9%, respectively. Furthermore, the carbon fiber–modified mixture exhibits the least favourable performance, indicating a negative environmental impact. Figure 5-h - indicates that the marine ecotoxicity potential (METP) increased with the incorporation of nano silica and carbon fiber by 7.8% and 22.62%, respectively, compared with the control mixture. Additionally, the combined additive led to a 30.63% increase in METP. Similarly, Figure 5-i shows that the terrestrial ecotoxicity potential (TETP) for mixtures modified with nano silica, carbon fiber, and their composite increased by 35.5%, 157%, and 225.5%, respectively, relative to CAM. Among all mixtures, the composite-modified asphalt exhibited the most unfavourable performance, as reflected by the highest TETP value. Figure 5-j shows that nano silica resulted in a slight increase in the POFP of 6.2% relative to the control mixture, whereas CFNSAM resulted in a 20.4% increase. In contrast, CFAM had the most pronounced effect, causing a 25% increase in CAM.

The comparative analysis of characterization results shows that none of the evaluated asphalt mixtures achieved environmental improvements across all impact categories. All modified mixtures exhibited negative effects relative to the control, although the differences were generally small. Among the additives, nano silica demonstrated the least adverse environmental performance in most impact categories, except for abiotic depletion potential (ADP). The composite-modified mixture produced the highest negative impacts in most categories. However, for GWP, ADP, OLD, FWETP, and POFP, the carbon fiber–modified mixture exhibited the greatest deterioration. Overall, POFP was the least affected impact category among all mixtures.

Figure 6 presents the relative variation of aggregated characterization results compared to the control mixture, where negative values indicate worsening environmental performance. The most pronounced negative variations were observed for ADP in the carbon fiber–modified and composite mixtures −851% and −436%, respectively, followed by OLD −541.5% and −222.4%, respectively. These extreme values largely dominated the results, reflecting the strong influence of carbon fiber on ADP and OLD.

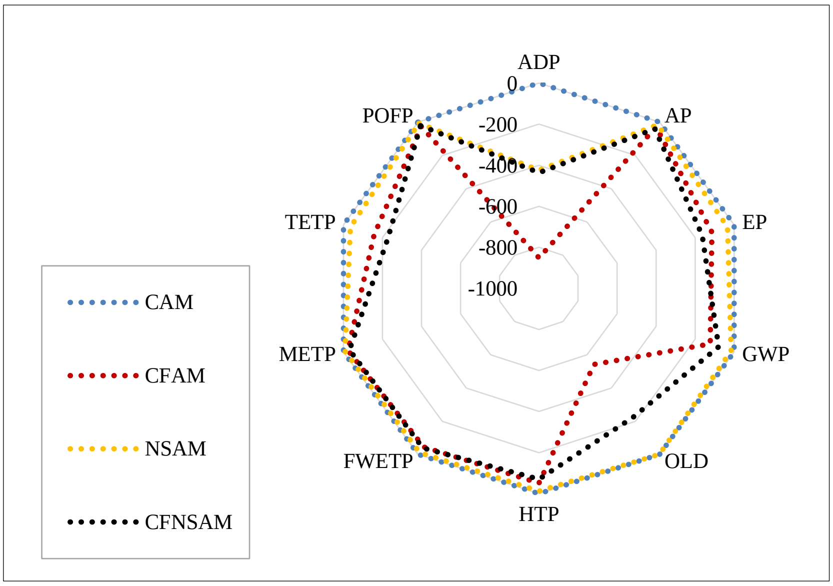


Figure 6. Relative variation of the LCIA for the compared mixtures

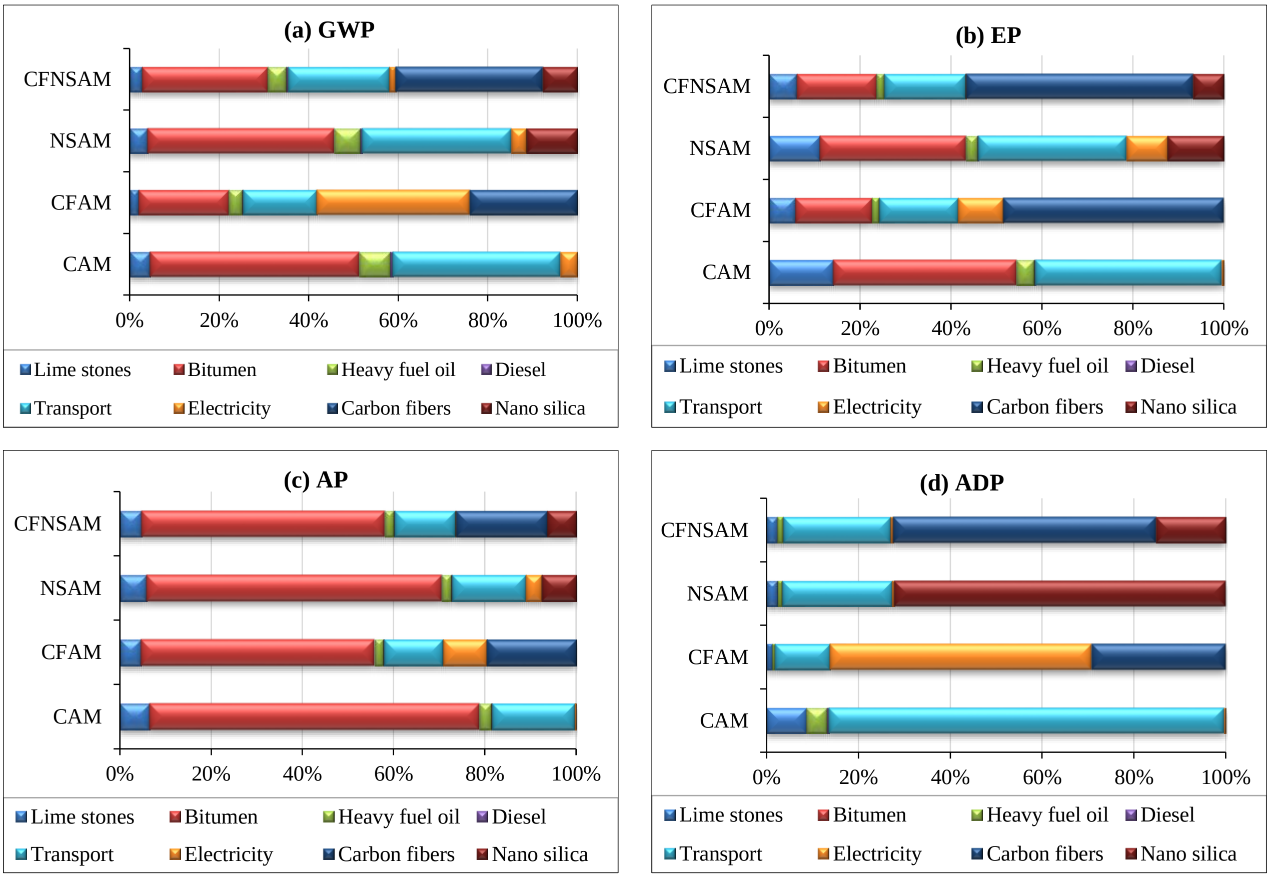
Nano silica enhances asphalt performance while maintaining a lower ecological footprint compared to carbon fiber additives. The environmental impact from nano silica comes from the manufacturing process, which uses chemicals such as sodium bicarbonate and sulfuric acid. These chemicals generate emissions and waste byproducts due to their corrosive nature and potential to cause acidification if released into the environment.

The significant environmental impact observed during the carbon fiber manufacturing process results from extensive use of hazardous chemicals and high energy consumption. Key substances such as acrylonitrile and dimethylacetamide are essential for producing carbon fibers and greatly contribute to the ecological footprint. Acrylonitrile, a toxic and volatile organic compound, presents risks due to potential air and water pollution during manufacturing and health hazards to workers if not properly controlled. Dimethylacetamide, used as a solvent, raises environmental and health concerns because of its toxicity and persistence in the environment. Besides chemical use, the production of carbon fibers demands large amounts of electricity and heat, often generated from non-renewable sources. This high energy demand leads to significant greenhouse gas emissions and other environmental impacts like GWP and AP. Together, these chemicals and energy-intensive processes cause considerable increases in ecological impact categories for carbon fiber-modified asphalt mixtures.

The results indicate that although the incorporation of nano silica causes a slight increase in environmental impacts compared to the control asphalt mix, its overall footprint is considerably lower than that of carbon fiber-based modifications. This distinction highlights the ecological benefits of using nano silica as an asphalt additive. Nano silica enhances the material's performance while minimizing environmental harm. Carbon fiber additives lead to substantially higher environmental burdens due to their more resource-intensive production and greater chemical usage. Therefore, nano silica presents a more sustainable option for enhancing asphalt properties without significantly compromising ecological integrity.

4.2. Process Contribution Analysis

Figure 7 shows that bitumen production, aggregate extraction, and asphalt mixture manufacturing are the dominant contributors to the environmental impact profiles of all asphalt mixtures. In contrast, processes such as carbon fiber and nano silica production, transportation, and wearing surface construction contribute only marginally to the overall impact scores. Bitumen production is the primary contributor to the global warming potential (GWP), acidification potential (AP), human toxicity potential (HTP), freshwater ecotoxicity potential (FWETP), marine ecotoxicity potential (METP), and photochemical ozone formation potential (POFP), as illustrated in Figures 7-a, 7-c, 7-e, 7-g, 7-h, and 7-j. Transport is a major contributor to the ADP and TETP, but its relative impact is reduced in the mixtures that include carbon fibers, as presented in Figures 7-d and 7-i, respectively. Carbon fiber production significantly increases EP impact in the asphalt mixtures containing carbon fibers, while bitumen and transport are the major contributors in other mixes, as shown in Figure 7-b. Figure 7-f demonstrates that heavy fuel oil, electricity, and transport are sharing in the rise of the OLD impact category.



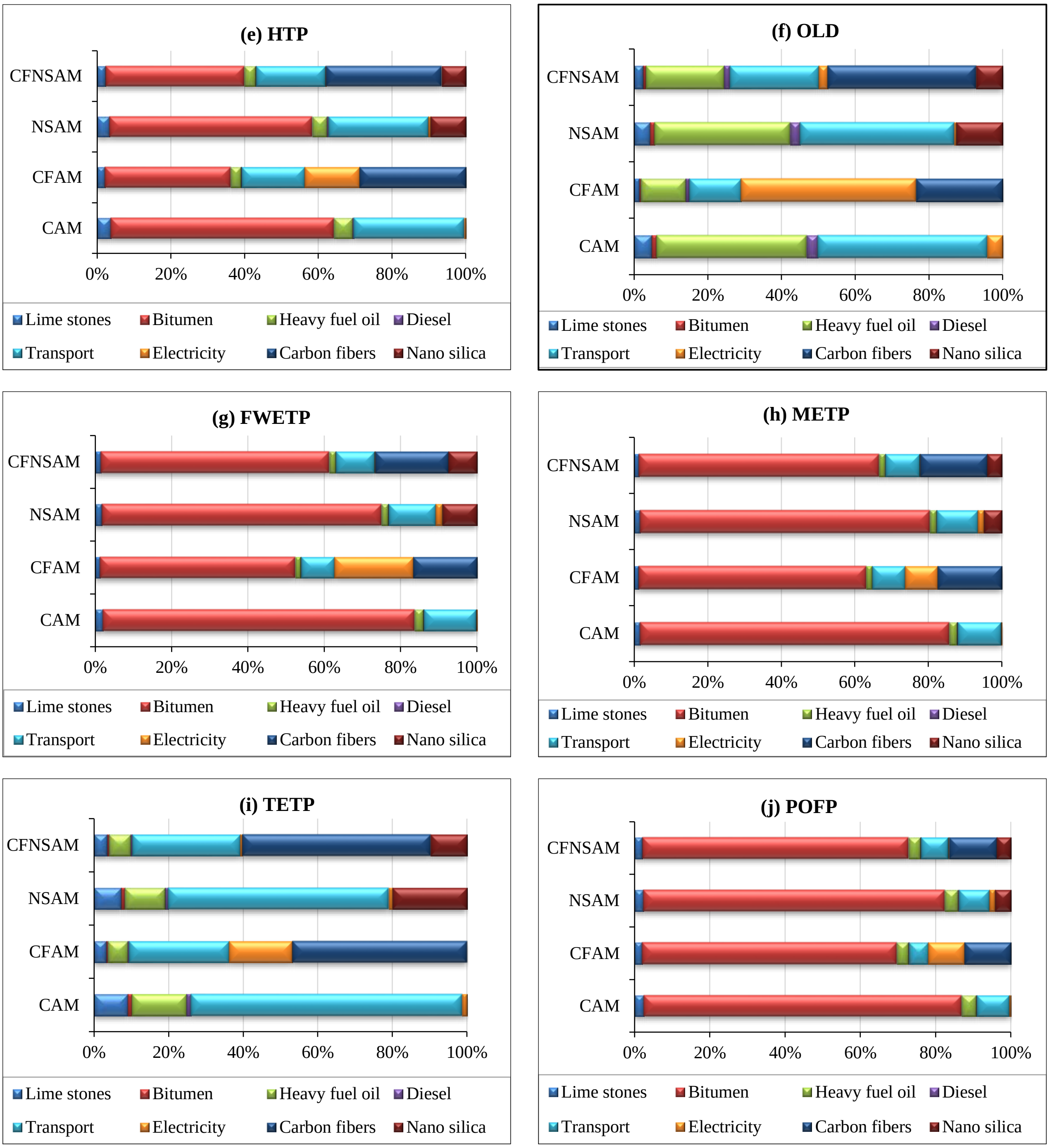


Figure 7. The relative contribution of the main processes to the total impact score

4.3. Comparison of the Contribution Result Analysis with Previous Studies

This section compares the contribution analysis results of the present study with findings reported in the LCA literature, with particular emphasis on the GWP category, which has been identified as the most influential impact indicator in previous studies. Ma et al. [28] conducted an integral LCA of warm mix asphalt and hot mix asphalt pavements, mentioning that raw material production, especially raw bitumen and bituminous asphalt, represents the most sensitive contributor to GWP.

Yue et al. [22] conducted a comparative LCA of asphalt mixtures modified with a diatomite–lignin fiber composite. Their findings showed that bitumen production was the dominant contributor to the AP, GWP, FWETP, ADP, EP, HTP, METP, and POFP categories, while aggregate extraction contributed most significantly to Terrestrial Ecotoxicity Potential (TETP).

Sackey et al. [15] evaluated an asphalt mixture modified with nano silica using life cycle assessment based on material-related emissions and compared the results with a control mixture to determine the contribution of nano silica.

Their findings indicated that adding nano silica led to a slight increase in the global warming potential of the modified asphalt mixture.

Boarie et al. [58] assessed the environmental performance of an asphalt mixture incorporating reclaimed asphalt pavement and waste polyethylene. The results showed that polyethylene and bitumen production dominate the environmental impact profile of the mixture. Polyethylene production contributed most significantly across all damage categories, human health, ecosystems, and natural resources, while electricity consumption during asphalt production had the smallest contribution to the overall impact.

Khater et al. [21] conducted an integral LCA of lignin fiber, glass fiber, and their composite modified asphalt mixtures. The results identified bitumen production as the primary contributor to ADP, AP, EP, GWP, FWETP, METP, and POFP. In contrast, asphalt mixture manufacturing dominated the ozone layer depletion (OLD) category, glass fiber production contributed most significantly to human toxicity potential (HTP), and aggregate extraction was the main contributor to terrestrial ecotoxicity potential (TETP).

The analysis of the studies above indicates that the results of the present work fall within the ranges reported in the literature. Consistent with previous findings, this study identifies bitumen production as the dominant contributor to both global warming potential and human toxicity potential.

4.4. Computation of Normalized Score

Figure 8 shows that METP contributes the most to the overall environmental impact of the reference community, making it the most critical impact category, followed by FWETP. The results further indicate that the asphalt mixtures perform relatively better only in four categories, ADP, EP, POFP, and OLD, where the normalized contributions represent a minimal share of the total environmental impacts. In contrast, GWP, AP, HTP, and TETP exhibit limited contributions to the overall impact profile, with only minor differences observed among the four asphalt mixtures across all impact categories.

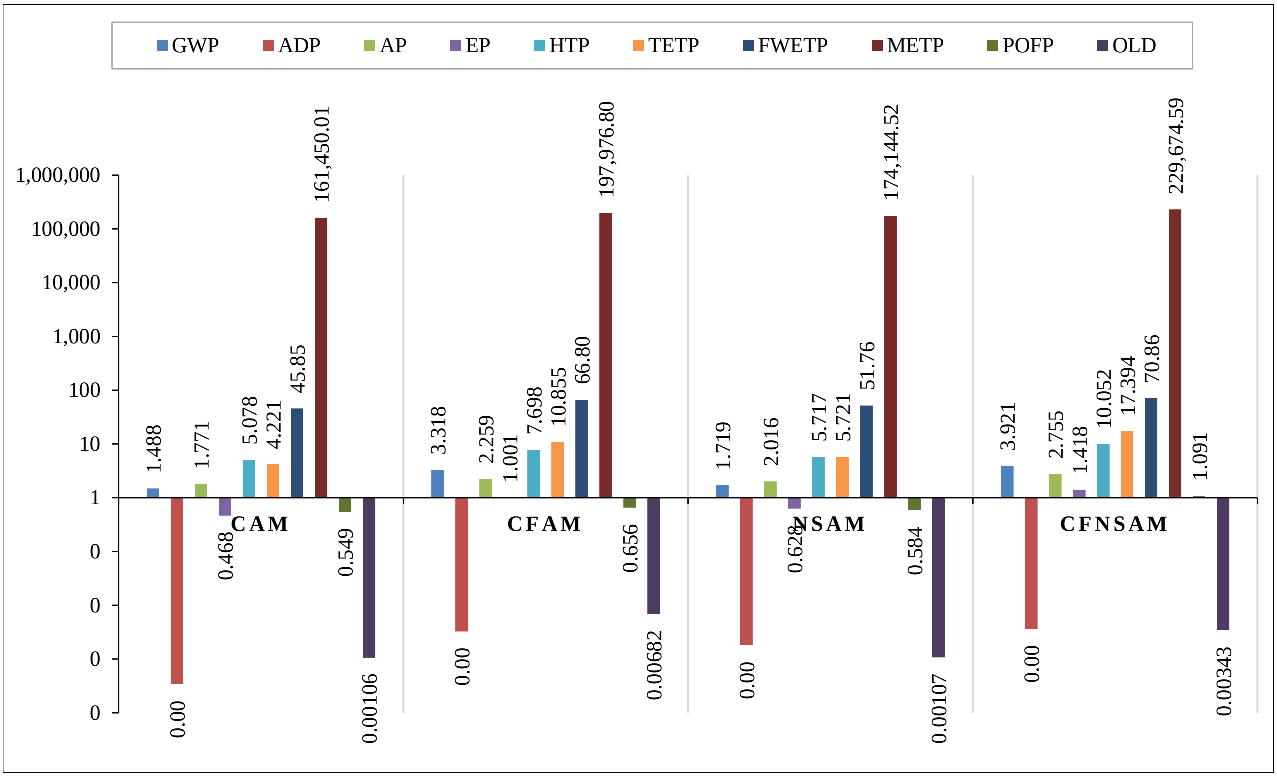


Figure 8. Normalization results of the compared mixtures

4.5. Weighting and Grouping

Figure 9 presents the weighted results of the LCA for the four asphalt mixtures, CAM, CFAM, NSAM, and CFNSAM, expressed in panel points $\times 10^{-10}$. The weighting phase in SimaPro integrates normalized environmental impacts with subjective value judgments or policy preferences, allowing for a single score that reflects the overall environmental burden of each alternative.

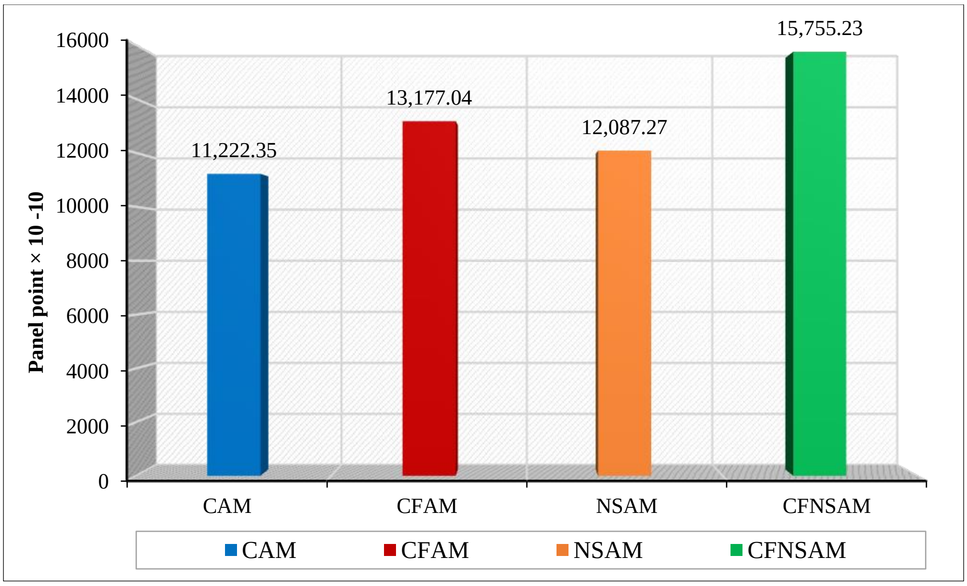


Figure 9. Weighting profiles of the asphalt mixtures by a panel method

The results indicate that CFNSAM has the highest weighted score [14,516.36 × 10⁻ ¹⁰], reflecting the greatest overall environmental impact among all mixtures. CFAM follows with a weighted score of 13,177.25 × 10⁻ ¹⁰ . This indicates that using carbon fibers alone also substantially increases the environmental burden. NSAM scores 12,082.20 × 10⁻ ¹⁰ , higher than the control mixture but notably lower than the fiber-containing alternatives. The lowest overall impact is observed in CAM [11,271.70 × 10⁻ ¹⁰], the control asphalt mixture without any additives.

These findings indicate that incorporating carbon fiber, either alone or combined with nano silica, results in substantially higher environmental impacts than the control asphalt mix (CAM). The nano silica-modified asphalt mixture (NSAM) demonstrates only a moderate increase in weighted impact relative to CAM. This underscores the role of nano silica as a more environmentally favourable additive. Nano silica offers performance benefits with comparatively lower environmental costs. Its balanced profile suggests nano silica provides an effective option for enhancing asphalt properties while minimizing adverse ecological effects.

4.6. Sensitivity Analysis

To examine the robustness of the LCA results, a one-factor-at-a-time sensitivity analysis was performed on key input parameters of the life-cycle inventory. The parameters analysed included energy consumption during carbon fiber production, Nano silica content in the asphalt mixture, and transportation distance of raw materials.

Each parameter was independently varied by ±20% while maintaining all other inputs constant. The results indicated that the environmental impact categories most sensitive to input variations were (GWP) and Cumulative Energy Demand (CED). A 20% increase in energy requirements for carbon fiber production resulted in approximately a 12% increase in total GWP for CFNSAM, confirming that energy consumption in carbon fiber manufacturing is the dominant uncertainty driver. In contrast, variations in nano silica dosage or transport distance produced a limited influence <5% on total impact values.

These results demonstrate that while some environmental indicators are sensitive to assumptions related to carbon fiber production, the overall ranking and comparative trends among the four asphalt mixtures (CAM < NSAM < CFAM < CFNSAM) remain consistent. Consequently, the main conclusions of this study are robust to reasonable variations in the life-cycle inventory assumptions.

5. Conclusions

For the development of the wearing surface of an Egyptian road pavement section, the environmental impact and contribution of additives in the asphalt mixture based on the LCA approach were examined, assessed, and contrasted with the control asphalt mixture. Three modified asphalt mixtures, carbon fiber, nano silica, and composite, were investigated in this study. The production of raw materials, the manufacturing of asphalt mixtures, the transportation of materials, and the building of wearing surfaces comprise the four primary phases of the life cycle of the road pavement manufacturing process. The production of asphalt mixes; The literature and the current Ecoinvent database V3.6 provided all of the background process data. The SimaPro 9.6 program was utilized in accordance with ISO 14040 and 14044 requirements to model and characterize the environmental characteristics of the various asphalt mixtures. A summary of the main findings is provided as follows:

- The three modified asphalt mixtures have a little negative effect in all impact categories, except the ADP and OLD impact categories, in the carbon fiber and composite modified asphalt mixture, with a great difference from the control asphalt mixture.
- All investigated mixtures do not present any enhancement in all impact categories.
- Except for GWP, ADP, OLD, FWETP, and POFP, where the carbon fiber-modified asphalt mixture has the most negative effect, the composite mixture has the greatest negative effect across all categories.
- Of all the environmental impact categories, the asphalt mix treated with nano silica has the least detrimental effect.
- For the effect categories HTP, AP, METP, GWP, FWETP, and POFP, the bitumen production process contributes the most. Additionally, the transportation process contributes the most to the OLD effect category. Furthermore, the carbon fiber manufacturing process contributes the most to the TETP and EP impact categories. Lastly, the production process for carbon fiber and nano silica contributes the most to the ADP impact category.

Finally, despite the increased environmental burden, the composite asphalt mixture demonstrates superior mechanical performance, supporting its potential application in pavement engineering.

6. Declarations

6.1. Author Contributions

Conceptualization, M.A. and M.S.E.; methodology, M.M.S. and M.A.; software, M.M.S. and M.A.; validation, M.A. and M.S.E.; formal analysis, M.M.S., M.A., and M.S.E.; investigation, M.M.S.; data curation, M.M.S. and M.S.E.; writing—original draft preparation, M.M.S.; writing—review and editing, M.A., A.G., and M.S.E.; visualization, M.A.; supervision, M.A. and A.G. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding Sources

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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