

A Performance Indicator Framework for Green Road Infrastructure toward the Sustainable Development Goals

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ABSTRACT

Road infrastructure supports connectivity, mobility, economic growth, and social accessibility, but its development can increase resource consumption, greenhouse gas emissions, and environmental pressure. Green road infrastructure integrates transportation functions with ecosystem services to promote sustainable development. This study develops a conceptual framework and performance indicators for evaluating green road infrastructure and its contribution to the Sustainable Development Goals (SDGs). A qualitative conceptual design was adopted through a structured review of 21 scientific and institutional sources. Based on sustainability assessment systems, road life-cycle approaches, and the DPSIR framework, the study develops 30 indicators across ecological, health, socio-cultural, and economic dimensions. The indicators are linked to 11 SDGs through 47 indicator-SDG relationships, with the strongest contributions to SDG 11, SDG 3, and SDG 9. The framework provides a basis for assessment and stakeholder decision-making.

INTRODUCTION

Mobility is a fundamental component of social and economic activity, and the development of road networks plays a critical role in supporting the movement of people and goods. However, the construction and maintenance of road infrastructure require large quantities of materials and energy and can generate substantial greenhouse gas (GHG) emissions (Ruiz & Guevara, 2020; Rousseau et al., 2022). The expansion of road networks can also lead to increased impervious surface cover, habitat fragmentation, and land-use change (Rousseau et al., 2022; Zheng et al., 2021). Population growth and urbanization increase material consumption and carbon emissions, making it increasingly important to decouple improvements in accessibility from growth in emissions in order to support climate change mitigation (Wenz et al., 2020; Rousseau et al., 2022). In light of this, researchers and transportation agencies have begun to explore road development concepts that move beyond a single function, instead integrating multiple functions with ecosystems and the environment.

Unlike *grey infrastructure*, which is designed with a narrow focus on specific technical aspects, the development of *green road infrastructure* corridors places greater emphasis on integrating roadside vegetation, permeable surfaces, *swales*, road shoulders, and active mobility facilities to support transportation functions while simultaneously generating a range of ecosystem services, including regulating, supporting, provisioning, and cultural services (Phillips et al., 2020; Rispoli & Ajibade, 2024). Ecosystem services are the benefits that humans derive from ecosystems (Millennium Ecosystem Assessment, 2005). By integrating road infrastructure with ecosystem services, road development can generate added value for road users and the environment through improvements in environmental quality, security, safety, comfort, and health, as well as through achieving sustainable road transportation.

Problem Statement and Research Gap

In sustainable transportation planning, the ability to develop indicators for assessing the sustainability of road assets based on spatially and temporally measurable criteria is essential. Various sustainability measurement models have been developed as tools for evaluating levels of sustainability, yet no widely accepted model has proven both comprehensive and integrative across the engineering, environmental, social, and economic functions of road corridors (Mehraban et al., 2025; Rageh et al., 2026).

Three gaps can be identified in the existing literature. First, established rating systems assess roads primarily as construction projects and assign uneven weights across the sustainability pillars, with ecosystem services and biodiversity remaining underrepresented (Mehraban et al., 2025). Second, criteria related to adaptation, precaution, and intergenerational equity are rarely operationalized in road sustainability indicator sets (Suprayoga et al., 2020). Third, although roads are explicitly linked to SDG targets 9.1 and 11.2, few frameworks translate corridor level performance into measurable contributions to multiple SDGs. Accordingly, this study addresses three research questions: 1. How can the causal relationships between road development, ecosystem services, ecosystem health, and human well-being be structured into a conceptual framework for green road

infrastructure? 2. Which performance indicators can be used to evaluate green road infrastructure across the ecological, health, socio-cultural, and economic dimensions? 3. How do these indicators contribute to the achievement of the SDGs?

Research Objectives, Novelty, and Contributions

This research therefore aims to (1) review existing frameworks for assessing the sustainability of road infrastructure, (2) synthesize conceptual models linking roads to ecosystem and human health, and (3) develop a set of performance indicators for multifunctional green road infrastructure that is mapped to the SDGs. The novelty of this study lies in nesting the DPSIR causal chain within the overlap of ecosystem services, ecosystem health, and human health and well-being, and in pre-mapping each indicator to the SDG(s) it most directly supports. The study contributes theoretically by providing an integrative framework that treats road corridors as multifunctional ecological infrastructure rather than single-purpose transport assets, and practically by offering transportation agencies and planners a traceable indicator set that can support design comparison, benchmarking, and SDG reporting.

This paper is organized as follows. Section 2 reviews the relevant literature; Section 3 describes the research design and the data collection and analysis procedures; Section 4 presents and discusses the conceptual framework, the indicator set, its alignment with the SDGs, and its theoretical and practical implications; and Section 5 concludes the paper and outlines its limitations and directions for future research.

THEORETICAL REVIEW

This section reviews the literature that motivates and informs the conceptual framework developed in Section 4. It first examines existing indicator-based and causal-chain frameworks for assessing road sustainability (Section 2.1), then reviews rating systems and quantitative models developed specifically for green road infrastructure (Section 2.2), situates green road development within the 2030 Agenda for Sustainable Development (Section 2.3), and concludes with a synthesis of the research gaps that inform the framework (Section 2.4).

Existing Frameworks for Assessing Road Infrastructure Sustainability

Since sustainable development entered the policy mainstream (World Commission on Environment and Development, 1987), indicator-based assessment has become the dominant method for evaluating the condition of, and changes in, the built and natural environment. In the transportation sector, sustainability assessment can be divided into two main approaches. The first uses rating systems designed specifically for civil and road infrastructure, which assess projects by awarding credits when design and construction practices support sustainable infrastructure development. The second comprises assessment methods and modeling tools used in planning and decision-making, which apply explicit criteria to compare options (Suprayoga et al., 2020).

The selection and organization of indicators is often structured around causal chain logic. The pressure–state–response (PSR) model proposed by the OECD (1993) distinguishes between pressures arising from human activity, the resulting environmental conditions, and society's response to environmental change. The European Environment Agency extended this model into the now widely recognized driving force–pressure–state–impact–response (DPSIR) framework, in which underlying driving forces generate pressures that alter environmental conditions, producing impacts on ecosystems and humans, which are in turn addressed by institutions through targets, standards, and monitoring (Niemeijer & de Groot, 2008). Applied to roads, this logic explains how demographic and economic driving forces are translated, through construction and traffic pressures, into changes in air, water, soil, microclimate, and habitat, which affect ecosystem and human health.

A systematic review of road sustainability indicators found that, although environmental and resource-efficiency criteria have become mainstream, criteria such as adaptation, precaution, and intergenerational equity are rarely operationalized, and recommended combining assessment tools or adopting an integrated indicator set for comprehensive coverage (Suprayoga et al., 2020). A more recent comparative analysis of rating systems reached a similar conclusion: among eight leading systems, environmental and social credits dominate while the economic dimension receives comparatively little weight, and ecosystem services and biodiversity considerations remain underrepresented (Mehraban et al., 2025).

Existing Models and Rating Systems for Green Road Infrastructure

Established sustainability assessment frameworks, including Greenroads, INVEST, CEEQUAL, and Envision, provide systematic criteria for evaluating material use, energy consumption, emissions, water management, ecological performance, and social outcomes in road infrastructure development (Mehraban et al., 2025). Despite their contributions, these frameworks often apply inconsistent weighting across indicators and primarily assess roads as construction projects rather than as integral components of broader landscape systems. Recent studies have therefore introduced quantitative approaches, including composite indices based on the *triple bottom line*, fuzzy multi-criteria methods, and frameworks that integrate least-cost route selection with sustainability assessment (Rageh et al., 2026; Samy et al., 2025). Nevertheless, further research is needed to develop an integrated assessment framework that incorporates environmental, social, economic, spatial, and ecological dimensions to provide a more comprehensive evaluation of road corridor sustainability.

Alongside these engineering-oriented tools, the ecological literature has shown that land within and around the road corridor is, in fact, ecologically active. Road verges can provide measurable ecosystem services pollination, carbon storage, pollutant capture, stormwater regulation, and habitat connectivity and can function as corridors that support biodiversity in otherwise fragmented landscapes, provided they are appropriately designed and managed (Phillips et al., 2020). Life-cycle studies add a further dimension, quantifying embodied carbon, energy, and material costs of pavements, and showing that

recycled and low-temperature mixes can substantially reduce environmental burdens compared with conventional materials (Rispoli & Ajibade, 2024; Aryan et al., 2023). On the human side, scoping and systematic reviews link mobility infrastructure that supports walking and cycling to protective effects on cardiovascular and respiratory health, fitness, and quality of life, together with additional environmental and economic benefits from reduced motorized travel (Michel et al., 2024). Table 1 summarizes and evaluates these complementary approaches.

Table 1. Comparison of representative approaches for assessing road infrastructure sustainability.

Tool/source	Scope & method	Sustainability coverage	Identified limitations
Greenroads; INVEST; CEEQUAL; Envision (Mehraban et al., 2025)	Credit-based rating system for road design, construction, and operation	Strong on environmental and social credits; weak on economic valuation	Voluntary credits unevenly weighted; limited ecosystem-service and biodiversity metrics
Integrated indicator set (Suprayoga et al., 2020)	Systematic review coding indicators against core sustainability criteria	Ten indicator groups across three pillars and the project life cycle	Adaptation, precaution, and intergenerational equity rarely operationalized
Green Proforma / fuzzy index (Rageh et al., 2026)	Expert-weighted triple-bottom-line rating for highways	Balances social, economic, and environmental factors with SDG alignment	Context-specific weighting; requires calibration across road typologies
Relative Sustainability Scoring Index (Samy et al., 2025)	Least-cost route planning combined with a composite sustainability index	Combines environmental impact and route efficiency at the planning stage	Focused on alignment selection; limited treatment of operational green elements
Pavement life-cycle assessment (Rispoli & Ajibade, 2024; Aryan et al., 2023)	ISO-based LCA/LCCA for pavement materials and systems	Quantifies embodied carbon, energy, and cost across all stages	Material-centred; underrepresents corridor ecology and human health outcomes

Overall, this comparison indicates that no existing road sustainability assessment model fully integrates engineering performance, the ecological functions of the corridor, and the associated health and economic outcomes for surrounding communities. Integrating the concept of ecosystem services with road assessment and life-cycle approaches would yield a more comprehensive assessment of sustainable road construction.

The Relationship between Green Road Development and the Sustainable Development Goals

The 2030 Agenda for Sustainable Development establishes seventeen Sustainable Development Goals (SDGs) that integrate the concept of infrastructure with environmental, social, and economic dimensions. Roads are

one form of infrastructure that contributes explicitly to the achievement of the SDGs: namely SDG 9 (Industry, Innovation, and Infrastructure, target 9.1 on reliable, resilient, and sustainable infrastructure) and SDG 11 (Sustainable Cities and Communities, target 11.2 on safe, affordable, and accessible transport systems), while the resource, emission, and land-use consequences of road construction relate to SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land).

Conventional grey road development tends to address these goals narrowly, since the road body serves only a single function advancing mobility-related targets, while simultaneously contributing to pressures such as land-use conversion, surface imperviousness, and emissions that work against climate and biodiversity objectives. Through the concept of green road construction, the multifunctionality of roads is integrated with the environment roadside vegetation, permeable surfaces, swales, and connected active-mobility facilities so that the same asset can provide regulating and supporting ecosystem services. Through this multifunctionality, road infrastructure contributes indirectly to other development goals: advancing SDG 3 (Good Health and Well-Being) through active mobility and cleaner air; SDG 7 (Affordable and Clean Energy) and SDG 13 through reduced embodied and operational emissions; SDG 8 (Decent Work and Economic Growth) through life-cycle cost savings and local economic activity; and SDG 10 (Reduced Inequalities) through more equitable access to safe, green mobility. Integrating green road development with the achievement of the SDGs is an effort to evaluate the extent to which road construction contributes at the spatial and local level, so that progress toward global targets can be assessed.

Synthesis of the Literature and Research Gap

Taken together, the literature reviewed in Sections 2.1–2.3 yields three insights that directly shape the framework developed in this study. First, causal-chain models such as PSR and DPSIR offer a robust logic for linking human activity to environmental and social outcomes, but in road studies they are rarely connected to the ecosystem services that the corridor itself can provide. Second, rating systems and quantitative models (Table 1) are strong on material, energy, and emission criteria but underrepresent ecosystem services, biodiversity, human health, and equity (Suprayoga et al., 2020; Mehraban et al., 2025). Third, although the contribution of roads to SDG 9 and SDG 11 is widely acknowledged, the indirect contributions of multifunctional road corridors to other goals, such as SDG 3, SDG 6, SDG 13, and SDG 15, are seldom measured at the project level.

These gaps suggest that a comprehensive assessment should (a) retain the DPSIR causal logic, (b) embed the domains of ecosystem services, ecosystem health, and human health and well-being within the impact stage (Tzoulas et al., 2007; Pakzad & Osmond, 2016), and (c) link each resulting indicator to specific SDGs. These three requirements form the analytical basis of the methodology described in Section 3 and of the framework presented in Section 4.

METHODOLOGY

Research Design

This study employs a qualitative, conceptual research design based on a structured literature review. No primary field data, respondents, or statistical sampling were involved; instead, previously published literature served as the unit of analysis for constructing a framework linking green road infrastructure with ecosystem services, ecosystem health, and human well-being. This study also produces performance indicators linked to the Sustainable Development Goals (SDGs). The research was carried out in three sequential stages: (1) literature search and data collection, (2) thematic analysis and framework development, and (3) indicator selection and SDG mapping. Each stage is described below in sufficient detail to allow the procedure to be replicated.

Data Collection Procedure

Data were collected through a structured literature search, as summarized in Table 2. The keywords "road infrastructure," "green infrastructure," "sustainability indicators," "ecosystem services," "DPSIR," and "Sustainable Development Goals" were combined using the Boolean operators AND/OR and searched in [database names – to be confirmed by the author] and on the websites of the OECD and the United Nations in [month and year of the search – to be confirmed by the author], supplemented by backward citation tracking to retrieve foundational documents. Records were screened by title and abstract and then by full text. Sources were included if they addressed the sustainability, environmental impacts, ecosystem services, or health outcomes of road or transport infrastructure, or provided a foundational framework; were peer-reviewed articles or reports and books from recognized international institutions; and were written in English. Studies limited to the structural or pavement-engineering performance of roads and sources without accessible full text were excluded. The final corpus comprised 21 sources published between 1987 and 2026 (17 journal articles and 4 institutional reports or books), of which 16 (76%) were published in 2016–2026.

Table 2. Literature search and data collection protocol.

Component	Description
Research design	Qualitative, conceptual study based on a structured literature review
Unit of analysis	Published scientific articles, institutional reports, and policy documents
Keywords	"road infrastructure," "green infrastructure," "sustainability indicators," "ecosystem services," "DPSIR," "Sustainable Development Goals" (combined with AND/OR)
Sources searched	[Databases – to be confirmed by the author]; websites of international institutions; backward citation tracking
Inclusion criteria	Road/transport sustainability, ecosystem services, or health outcomes, or foundational frameworks; peer-reviewed articles or institutional reports/books; English language

Component	Description
Exclusion criteria	Purely structural or pavement-engineering studies without a sustainability dimension; full text not accessible
Final corpus	21 sources (1987–2026): 17 journal articles and 4 institutional reports/books; 16 sources (76%) published in 2016–2026
Data extraction fields	Framework/method; sustainability dimensions; criteria/indicators; ecosystem-service and health evidence; SDG linkage
Data analysis	Two-cycle thematic coding against the DPSIR elements and the three domains of ecosystem services, ecosystem health, and human health and well-being
Outputs	Conceptual framework (Figures 1–2); 30 indicators in four dimensions (Table 4); SDG mapping (Tables 4–5)

Source: author's research procedure.

Indicator Selection and SDG Mapping

Selected indicators were then identified from the coded data and grouped into four dimensions: ecological, health, socio-cultural, and economic. An indicator was retained only if it met four criteria: (i) relevance, meaning that it measures a function or outcome of the road corridor identified in the framework; (ii) evidence, meaning that it is supported by at least one scientific source in the corpus; (iii) measurability, meaning that it can, in principle, be quantified or qualitatively scored at the corridor scale; and (iv) non-redundancy, meaning that it does not duplicate another indicator in the set. Each retained indicator was assigned a code (E = ecological, H = health, S = socio-cultural, C = economic) and then mapped to the SDG(s) whose targets correspond to the outcome it measures, such as emission reduction (SDG 13), active mobility (SDG 3), or habitat connectivity (SDG 15). An indicator was mapped to more than one SDG only where the measured outcome contributes directly to the targets of each goal. Finally, the number of indicators linked to each SDG was tabulated to identify well-covered and underrepresented goals (Table 2).

RESULTS AND DISCUSSION

This section presents the three main findings of the study, each corresponding to one research question: the integrated conceptual framework (Finding 1, Section 4.1, RQ1), the performance indicator set (Finding 2, Section 4.2, RQ2), and the alignment of the indicators with the SDGs (Finding 3, Section 4.3, RQ3). Section 4.4 then discusses the theoretical and practical implications of these findings.

Finding 1: The Integrated Conceptual Framework

The DPSIR logic provides the underlying framework for linking human activity to the performance of green road infrastructure. Figure 1 illustrates these linkages: demographic and economic driving forces, together with physical drivers such as climate change, generate pressures (land-use conversion, expansion of impervious surfaces, emissions, resource use, noise, and runoff); these pressures alter corridor conditions (air, water, and soil quality; surface

temperature; vegetation and connectivity; hydrology; and travel-environment quality); the resulting impacts fall on ecosystem services, ecosystem health, and human health and well-being; and institutional responses design standards, indicators, targets, and monitoring provide feedback that reduces these driving forces and pressures.

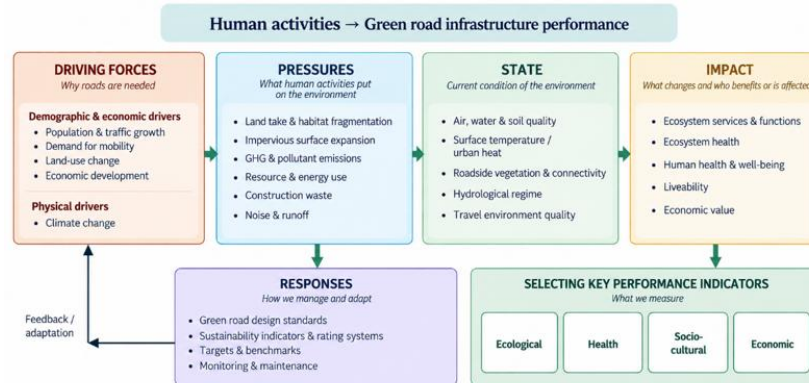


Figure 1. DPSIR framework illustrating the relationship between human activities and green road infrastructure performance (Source: adapted from OECD, 1993; Niemeijer & de Groot, 2008).

Figure 1 is read from left to right along the upper row (Driving Forces → Pressures → State → Impact). The Responses panel shows how institutions intervene through green road design standards, sustainability indicators and rating systems, targets and benchmarks, and monitoring and maintenance, while the feedback arrow from Responses to Driving Forces indicates that monitoring results are intended to inform adaptation. The Selecting Key Performance Indicators panel shows that indicators are derived from the impact stage and grouped into the four dimensions (ecological, health, socio-cultural, and economic) that are used in Section 4.2.

Within this causal structure, the impact stage is where sustainability is ultimately realized or lost, and this stage is governed by the interaction of three interrelated systems. Drawing on the integrated green infrastructure framework linking ecological concepts with human health (Tzoulas et al., 2007) and the indicator logic of Pakzad and Osmond (2016), Figure 2 depicts green road infrastructure as the overlapping zone between the ecosystem services of the road corridor, ecosystem health, and human health and well-being. A healthy, well-vegetated, and well-drained corridor enhances the provision of regulating, supporting, and cultural services, which in turn improves human health and economic value at both the individual and community scale. This framework accommodates both anthropocentric and ecocentric perspectives and provides the conceptual basis for identifying indicators within each domain.

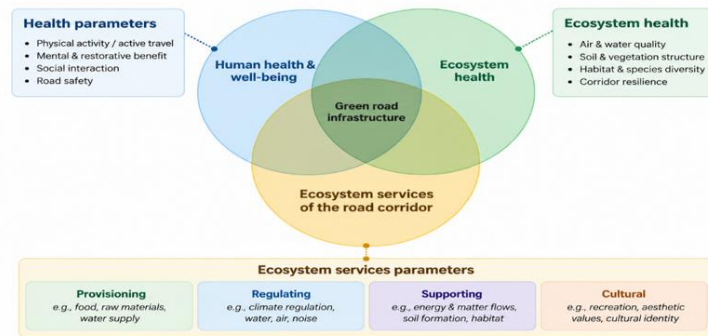


Figure 2. Integrated conceptual framework for green road infrastructure as the overlap of human health and well-being, ecosystem health, and ecosystem services of the road corridor (Source: adapted from Tzoulas et al., 2007; Pakzad & Osmond, 2016).

Figure 2 comprises three labeled domains. The human health and well-being domain (upper left) is characterized by health parameters (physical activity and active travel, mental and restorative benefits, social interaction, and road safety), which correspond to health indicators H1–H4. The ecosystem health domain (upper right) is described by air and water quality, soil and vegetation structure, habitat and species diversity, and corridor resilience, which underpin ecological indicators such as E2, E7, E8, and E10. The ecosystem services domain (bottom) is described by the four service categories of the Millennium Ecosystem Assessment (2005), namely provisioning, regulating, supporting, and cultural services, which are elaborated for road corridors in Table 3. Green road infrastructure occupies the central zone where the three domains overlap, indicating that a road corridor can be considered "green" only when it simultaneously sustains ecosystem health, delivers ecosystem services, and improves human health and well-being. In response to RQ1, this integrated framework constitutes the first finding of the study.

Finding 2: Green Road Infrastructure Performance Indicators

Indicators reduce data complexity, simplify interpretation and assessment, and facilitate communication between technical experts and decision-makers (Niemeijer & de Groot, 2008). For green road infrastructure, indicators are organized under the three triple-bottom-line principles, further divided into subdomains corresponding to environmental, social, and economic themes aligned with ecosystem services. Table 3 presents this first level of organization: for each theme, it lists the ecosystem-service subdomains that a green road corridor can provide, together with examples of the related road-corridor indicators.

Table 3. Ecosystem services provided by green road corridors, organized by the triple bottom line.

Theme	Subdomain	Road-corridor-related indicators
Environmental	Climate & microclimate regulation	Shading and evapotranspiration from roadside trees; reduction of surface temperature and urban heat
	Climate change mitigation	Carbon sequestration by roadside vegetation; avoided and embodied emissions from low-carbon pavements
	Air quality regulation	Capture of particulate and gaseous pollutants by corridor vegetation
	Hydrological regulation	Infiltration through permeable surfaces and swales; flow attenuation and runoff treatment
	Soil support & biodiversity	Erosion control on embankments; provision of habitat and ecological connectivity along road verges
Social	Health & well-being	Physical activity through active mobility; restorative and social value of green road landscapes; road safety
	Culture & aesthetics	Sense of place, visual quality, and recreational use of the corridor
Economic	Value creation & avoided costs	Increased property value; life-cycle cost savings; avoided grey-infrastructure and health costs

Source: *Millennium Ecosystem Assessment (2005), Phillips et al. (2020), Michel et al. (2024), and the studies listed in Table 1.*

By translating this typology of services into measurable performance, the conceptual framework supports four indicator dimensions ecological, health, socio-cultural, and economic that together capture the main benefits attributed to green road infrastructure in the literature. These benefits can be grouped into a set of recurring themes that the framework is designed to address:

1. Climate change mitigation and adaptation, including microclimate regulation and low-carbon materials;
2. Healthy ecosystems, biodiversity, and corridor connectivity;
3. Human health and well-being through active mobility and restorative green space;
4. Water management through infiltration, attenuation, and runoff treatment;
5. Economic value, including life-cycle cost savings and avoided grey-infrastructure and health costs;
6. Livability, accessibility, sense of place, and equitable, well-connected mobility.

Table 4. Proposed set of green road infrastructure performance indicators and their SDG alignment.

Code	Performance indicator	Reference	Sustainable Development Goals (SDGs) Alignment
Ecological indicators			
E1	Microclimate and urban heat mitigation (shading and evapotranspiration from roadside vegetation; reduction of surface temperature)	Mhana et al. (2024); Phillips et al. (2020)	SDG 11, 13
E2	Air quality improvement (pollutant removal and avoided emissions along the corridor)	Phillips et al. (2020); Suprayoga et al. (2020)	SDG 3, 11
E3	Carbon sequestration and avoided greenhouse gas emissions	Aryan et al. (2023); Rageh et al. (2026)	SDG 13
E4	Embodied carbon and life-cycle emissions of pavement materials	Rispoli & Ajibade (2024); Aryan et al. (2023)	SDG 9, 13
E5	Use of recycled, reclaimed, and low-impact materials (material circularity)	Rispoli & Ajibade (2024)	SDG 9, 12
E6	Stormwater regulation and flood reduction (permeable pavements, swales, SuDS)	Suprayoga et al. (2020); Samy et al. (2025)	SDG 6, 11
E7	Water quality protection and runoff treatment	Suprayoga et al. (2020)	SDG 6
E8	Soil quality and erosion control on verges and embankments	Phillips et al. (2020)	SDG 15
E9	Traffic noise attenuation by vegetation buffers	Mehraban et al. (2025)	SDG 3, 11
E10	Biodiversity and habitat connectivity along verges and corridors	Phillips et al. (2020)	SDG 15
Health indicators			
H1	Physical well-being through provision for active mobility (walking and cycling)	Michel et al. (2024)	SDG 3
H2	Mental and restorative benefits of roadside green landscapes	Michel et al. (2024); Tzoulas et al. (2007)	SDG 3
H3	Social well-being and community interaction in road spaces	Michel et al. (2024)	SDG 3, 11
H4	Road safety and reduced traffic injury risk	Suprayoga et al. (2020); Rageh et al. (2026)	SDG 3, 11
H5	Reduced population exposure to air and noise pollution	Michel et al. (2024)	SDG 3, 11

Code	Performance indicator	Reference	Sustainable Development Goals (SDGs) Alignment
Socio-cultural indicators			
S1	Connected active-mobility network (continuous cycling lanes and sidewalks)	Michel et al. (2024)	SDG 9, 11
S2	Accessibility and integration with other transport modes	Heidari et al. (2023)	SDG 9, 11
S3	Walkability and pedestrian environment quality	Michel et al. (2024)	SDG 11
S4	Community livability and reduced community severance	Suprayoga et al. (2020)	SDG 11
S5	Sense of place, road-landscape identity, and cultural value	Pakzad & Osmond (2016)	SDG 11
S6	Aesthetic quality and visual amenity of the corridor	Mehraban et al. (2025)	SDG 11
S7	Public participation and stakeholder engagement	Rageh et al. (2026)	SDG 16
S8	Intergenerational equity and equitable access	Suprayoga et al. (2020)	SDG 10, 11
Economic indicators			
C1	Life-cycle cost savings (construction, operation, and maintenance)	Aryan et al. (2023); Samy et al. (2025)	SDG 9, 12
C2	Avoided or reduced grey-infrastructure and drainage costs	Suprayoga et al. (2020)	SDG 9, 11
C3	Increased surrounding property value and land value capture	Heidari et al. (2023)	SDG 8, 11
C4	Local economic activity and tourism along greened corridors	Heidari et al. (2023)	SDG 8
C5	Health cost savings attributable to active mobility	Michel et al. (2024)	SDG 3
C6	Value of avoided emissions and reduced energy use	Rispoli & Ajibade (2024); Rageh et al. (2026)	SDG 7, 13
C7	Reduced congestion and travel-time costs through modal shift	Michel et al. (2024); Heidari et al. (2023)	SDG 9, 11

Note: E = ecological; H = health; S = socio-cultural; C = economic. Shaded rows mark the four indicator dimensions.

Source: compiled by the author from the literature cited in the Reference column.

As shown by the shaded dimension rows in Table 4, the proposed set comprises 30 indicators distributed across the four dimensions: 10 ecological indicators (E1–E10), 5 health indicators (H1–H5), 8 socio-cultural indicators (S1–S8), and 7 economic indicators (C1–C7). Each row provides the indicator code, a concise description of the aspect being measured, the source or sources from which the indicator was derived, and the corresponding Sustainable Development Goal(s) (SDGs). This structure ensures that each indicator can be systematically traced to the relevant supporting literature and clearly linked to the specific SDG(s) it addresses. The four dimensions are explained below.

Ecological indicators (E1–E10). The ecological dimension is the largest, reflecting the regulating and supporting services of the corridor. It covers climate regulation (E1, E3), air quality (E2), the carbon and material footprint of pavements (E4, E5), water management (E6, E7), soil protection (E8), noise attenuation (E9), and biodiversity and habitat connectivity (E10). Indicators E4 and E5 capture the life-cycle perspective emphasized in pavement LCA studies (Rispoli & Ajibade, 2024; Aryan et al., 2023), whereas E1, E8, and E10 operationalize the ecosystem functions of road verges documented by Phillips et al. (2020).

Health indicators (H1–H5). The health dimension translates the human health and well-being domain of Figure 2 into measurable outcomes: physical activity through active mobility (H1), mental and restorative benefits (H2), social well-being (H3), road safety (H4), and reduced exposure to air and noise pollution (H5). These indicators reflect evidence that mobility infrastructure supporting walking and cycling has protective effects on cardiovascular and respiratory health and on quality of life (Michel et al., 2024).

Socio-cultural indicators (S1–S8). This dimension addresses how the corridor functions as a social space: network connectivity and intermodal accessibility (S1, S2), walkability and livability (S3, S4), place identity and aesthetics (S5, S6), and governance and equity (S7, S8). Indicators S7 and S8 are particularly important because participation and intergenerational equity are rarely operationalized in existing assessment tools (Suprayoga et al., 2020).

Economic indicators (C1–C7). The economic dimension captures both direct financial benefits, namely life-cycle cost savings (C1) and avoided grey-infrastructure costs (C2), and wider economic value, including property value (C3), local economic activity (C4), health cost savings (C5), the value of avoided emissions and energy use (C6), and reduced congestion costs (C7). This dimension responds to the finding that economic valuation receives comparatively little weight in current rating systems (Mehraban et al., 2025). In response to RQ2, this 30-indicator set constitutes the second finding of the study.

Finding 3: Alignment of the Indicator Set with the Sustainable Development Goals

Because green road infrastructure sits at the intersection of environmental, social, and economic systems, the indicator set in Table 4 was cross-checked against the 2030 Agenda for Sustainable Development to clarify which SDGs are most directly supported by each indicator; the corresponding SDGs are reported in the right-hand column of Table 4. The ecological indicators (E1–E10) align

primarily with SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 15 (Life on Land), reflecting the corridor's role in regulating water, climate, and habitat; in addition, the material-related indicators E4 and E5 support SDG 9 and SDG 12 (Responsible Consumption and Production), and the air-quality and noise indicators E2 and E9 support SDG 3. The health indicators (H1–H5) support SDG 3 (Good Health and Well-Being) and, insofar as they reduce population exposure to traffic-related pollution and injury risk in urban environments, also contribute to SDG 11. The socio-cultural indicators (S1–S8) align primarily with SDG 9 (Industry, Innovation, and Infrastructure), SDG 10 (Reduced Inequalities), SDG 11, and SDG 16 (Peace, Justice, and Strong Institutions), reflecting their relation to connected and inclusive mobility networks, equitable access, and participatory corridor governance. The economic indicators (C1–C7) relate mainly to SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 9, and SDG 12, and secondarily to SDG 3 (C5), SDG 11 (C2, C3, C7), and SDG 13 (C6), capturing the efficiency, resource use, and revenue associated with greener road assets.

Table 5 summarizes the distribution of the 30 indicators across the SDGs

SDG	Number of indicators	Indicator codes	Share of the 30 indicators (%)
SDG 3 – Good Health and Well-Being	8	E2, E9, H1–H5, C5	26.7
SDG 6 – Clean Water and Sanitation	2	E6, E7	6.7
SDG 7 – Affordable and Clean Energy	1	C6	3.3
SDG 8 – Decent Work and Economic Growth	2	C3, C4	6.7
SDG 9 – Industry, Innovation and Infrastructure	7	E4, E5, S1, S2, C1, C2, C7	23.3
SDG 10 – Reduced Inequalities	1	S8	3.3
SDG 11 – Sustainable Cities and Communities	17	E1, E2, E6, E9, H3–H5, S1–S6, S8, C2, C3, C7	56.7
SDG 12 – Responsible Consumption and Production	2	E5, C1	6.7
SDG 13 – Climate Action	4	E1, E3, E4, C6	13.3
SDG 15 – Life on Land	2	E8, E10	6.7
SDG 16 – Peace, Justice and Strong Institutions	1	S7	3.3
Total	47 links	30 indicators (17 linked to two SDGs; 13 linked to one SDG)	–

Source: author's analysis of Table 4.

Three observations emerge from Table 5. First, the indicator set covers 11 of the 17 SDGs through 47 indicator–SDG links, confirming that green road infrastructure contributes to the 2030 Agenda well beyond the transport-related targets 9.1 and 11.2. Second, the contributions are concentrated: SDG 11 is linked to 17 indicators (56.7%), SDG 3 to 8 indicators (26.7%), and SDG 9 to 7 indicators (23.3%), reflecting the dominant role of roads as urban and community infrastructure and the strong evidence base on active mobility and health. Third, SDG 7, SDG 10, and SDG 16 are each supported by only one indicator (C6, S8, and S7, respectively), and SDG 6, SDG 8, SDG 12, and SDG 15 by two indicators each. These goals are therefore the least represented and indicate where the indicator set, and green road assessment more generally, requires further development, particularly with respect to energy efficiency, equity, and governance.

This mapping shows that the proposed indicator set is not only internally coherent across the ecological, health, socio-cultural, and economic dimensions, but also externally consistent with the global sustainability agenda, thereby offering transportation agencies a practical bridge between project-level performance monitoring and national SDG reporting. Because 17 of the 30 indicators contribute simultaneously to more than one goal (for example, the active-mobility indicators H1, S1, and S3 together advance SDG 3 and SDG 11, while the material-circularity indicators E5 and C1 together advance SDG 9 and SDG 12), the framework also illustrates the co-benefits and potential synergies of investing in green road infrastructure, rather than treating each pillar of sustainability in isolation. In response to RQ3, this SDG alignment constitutes the third finding of the study.

CONCLUSIONS AND RECOMMENDATIONS

Sustainability assessment aims to support decision-making by identifying, measuring, and comparing the environmental, social, and economic implications of a project or policy. Green road infrastructure performance indicators can play this role for the transportation sector. These indicators enable benchmarking against established targets, comparison of alternative design and management practices, and identification of best practices across different development scenarios.

This paper has proposed a conceptual framework linking the performance of green road infrastructure to ecosystem services, ecosystem health, and human health and well-being, embedded within the causal logic of DPSIR. From this framework, a set of thirty integrated indicators has been derived across the ecological, health, socio-cultural, and economic dimensions, each grounded in recent peer-reviewed evidence on road verges, sustainable pavements, rating systems, and the health outcomes of active mobility. The framework also integrates the Sustainable Development Goals, mapping the thirty indicators above into a conceptual structure for identifying specific indicators relevant to the achievement of the SDGs.

In answer to the three research questions, this study found that (1) the DPSIR causal chain can be integrated with the domains of ecosystem services, ecosystem health, and human health and well-being to form a coherent conceptual framework for green road infrastructure (Figures 1 and 2); (2) the performance of green roads can be captured by 30 literature-based indicators across four dimensions (Table 4); and (3) these indicators contribute to 11 SDGs through 47 indicator-SDG links, with the strongest contributions to SDG 11, SDG 3, and SDG 9 and the weakest to SDG 7, SDG 10, and SDG 16 (Table 5).

FURTHER STUDY

This study has several limitations. First, the framework and indicators were derived from a literature corpus of 21 sources and have not yet been validated by experts or applied to real road corridors. Second, the indicators are not weighted, and measurement units, data sources, and threshold values have not yet been specified for each indicator. Third, the SDG mapping was performed at the goal level and relies on the author's judgment of the outcome measured by each indicator. Future research should therefore (i) validate and weight the indicators through expert-based methods such as the Delphi technique or the analytic hierarchy process, (ii) define measurement protocols and benchmark values for each indicator, (iii) test the framework through case studies on urban and rural road corridors, including in Indonesia, and (iv) refine the mapping to the level of specific SDG targets.

Future research should focus on empirically validating the proposed performance indicators through field-based assessments of green road infrastructure in different geographical and socioeconomic contexts. The indicators developed in this study provide a conceptual foundation, but their practical applicability should be examined using real-world road projects and measurable sustainability data. Such validation can help determine the reliability, sensitivity, and relevance of each indicator for different types of road infrastructure.

Further studies may also develop a composite assessment model by assigning appropriate weights to the 30 indicators based on stakeholder preferences, expert judgment, and quantitative analytical methods. Integrating methods such as the Analytical Hierarchy Process, multi-criteria decision analysis, structural equation modeling, or other decision-support approaches could provide a more systematic means of measuring overall green road infrastructure performance. The development of standardized scoring procedures would also facilitate comparisons among road projects and regions.

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