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ENVIRONMENTAL MONITORING AND STRATEGIES FOR MINIMIZING THE IMPACT OF TRANSPORT INFRASTRUCTURE ON THE ENVIRONMENT

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The relevance of this study is driven by the increasing anthropogenic pressure of the transport sector on the environment amid the intensification of freight and passenger transportation and the expansion of road transport infrastructure. The aim of the work is to develop a conceptual strategic model of environmental sustainability for transport enterprises, integrating subsystems of environmental monitoring, risk management, and minimization of negative impacts on ecosystems. To achieve this aim, the methods of systems analysis, comparative assessment, analytic hierarchy process, and strategic planning were applied. The methodological framework is grounded in sustainable development principles and the concept of corporate environmental responsibility. The scientific novelty lies in synthesizing strategic management theory with environmental engineering practice, producing a multi-level model that explicitly links monitoring data feedback loops with technology selection decisions and enterprise-level sustainability targets. The results obtained encompass an original three-level strategic model of environmental sustainability for transport enterprises, structured across the strategic level (enterprise-wide policy and long-term targets), the tactical level (integrated environmental monitoring and performance management), and the operational level (technology selection, infrastructure management, and daily emission control), connected through defined feedback mechanisms. An integrated environmental monitoring algorithm was developed, comprising six sequential process blocks – from parameter identification and sensor network design to management reporting – with early-warning thresholds set at 80% of regulatory limit values. A system of criteria for evaluating ecologically safe technologies and materials in road construction was proposed, anchored by a composite Technology Sustainability Score (*TSS*) calculated across five AHP-weighted evaluation dimensions. The practical value of the study lies in the potential for direct application of the proposed model by road transport enterprises and road construction organizations for the formation and implementation of environmental sustainability strategies, reduction of air, soil, and water pollution, and optimization of environmental monitoring systems in accordance with current legislation and international standards. The proposed strategic model addresses the gap between regulatory compliance and proactive environmental management, providing a replicable framework adaptable to diverse transport enterprise contexts. *Key words:* transport enterprise, enterprise sustainability, transport infrastructure, environmental monitoring, strategy, ecologically safe technologies, road construction.

Екологічний моніторинг та стратегії мінімізації впливу транспортної інфраструктури на довкілля. Луньова О.В.
Актуальність дослідження обумовлена зростаючим антропогенним тиском транспортної галузі на навколишнє середовище в умовах інтенсифікації перевезень та розвитку дорожньо-транспортної інфраструктури. Мета роботи полягає у розробленні концептуальної стратегічної моделі екологічної стійкості транспортного підприємства, що інтегрує підсистеми моніторингу довкілля, управління ризиками та мінімізації негативного впливу на екосистеми. Для досягнення мети застосовано методи системного аналізу, порівняльного оцінювання, аналізу ієрархій та стратегічного планування. Методологічну основу становлять принципи сталого розвитку та концепція корпоративної екологічної відповідальності. Наукова новизна полягає у поєднанні теорії стратегічного управління з практикою екологічного інжинірингу, що дало змогу побудувати багаторівневу модель із явним зв'язком між зворотними потоками даних моніторингу, вибором технологій та цільовими показниками стійкості підприємства. Отримані результати охоплюють авторську трирівневу стратегічну модель екологічної стійкості транспортного підприємства, яка об'єднує стратегічний рівень (політика та довгострокові цілі), тактичний рівень (інтегрований моніторинг довкілля та управління ефективністю) й операційний рівень (вибір технологій, управління інфраструктурою, контроль викидів) через механізми зворотного зв'язку. Розроблено алгоритм інтегрованого моніторингу довкілля, що складається із шести послідовних блоків – від ідентифікації параметрів і проєктування мережі датчиків до формування управлінської звітності з пороговими значеннями раннього попередження на рівні 80% від нормативних лімітів. Запропоновано систему критеріїв оцінювання екологічно безпечних технологій і матеріалів у дорожньому будівництві на основі композитного показника екологічної стійкості технології (*TSS*), розрахованого за п'ятьма зваженими вимірами методом аналізу ієрархій. Практична цінність дослідження полягає в можливості безпосереднього застосування запропонованої моделі підприємствами автомобільного транспорту та дорожньо-будівельними організаціями для формування та реалізації стратегій екологічної стійкості, зниження рівня забруднення повітря, ґрунтів і водних об'єктів, а також оптимізації системи екологічного моніторингу відповідно до вимог чинного законодавства та міжнародних стандартів. *Ключові слова:* транспортне підприємство, стійкість підприємства, транспортна інфраструктура, моніторинг довкілля, стратегія, екологічно безпечні технології, дорожнє будівництво.

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Introduction. The global transport sector currently accounts for approximately 23% of total energy-related CO_2 emissions, a figure projected to grow in parallel with urbanization and freight intensification trends [1]. Road transport, as the dominant mode, contributes disproportionately to local air quality degradation, soil contamination through runoff and spill events, noise pollution, and the fragmentation of natural habitats through infrastructure expansion. These pressures collectively underscore the urgency of developing coherent, enterprise-level strategies that move beyond regulatory compliance toward proactive environmental stewardship. Transport enterprises occupy a strategically important position in addressing environmental challenges: they simultaneously generate pollution through fleet operations and serve as implementers of road construction and maintenance activities that directly affect land use, hydrological systems, and biodiversity. Consequently, the concept of enterprise sustainability in the transport sector encompasses not only economic viability and social responsibility but critically includes the systematic management of environmental performance across the full operational lifecycle [2].

Environmental monitoring constitutes a foundational element of any effective sustainability strategy. For transport enterprises, monitoring must address emissions to air from vehicle exhausts and construction machinery, leachate and stormwater quality from road surfaces and depots, soil quality at operational sites, noise levels along transport corridors, and biodiversity indicators in sensitive zones adjacent to infrastructure. The integration of monitoring data into strategic decision-making cycles, however, remains inconsistent across the industry, particularly among small and medium transport operators. In the context of road construction and maintenance, the selection of technologies and materials carries significant environmental implications. The increasing availability of recycled and warm-mix asphalt technologies, bio-based binders, permeable pavements, and low-carbon concrete alternatives creates both opportunities and decision complexity for enterprise planners [3]. A systematic criterion framework for technology selection, anchored in environmental impact categories and aligned with enterprise sustainability objectives, is therefore a practical necessity.

The aim of this study is to develop a strategic model for the environmental sustainability management of transport enterprises that integrates environmental monitoring, ecologically safe technology selection, and strategic planning into a unified, operational framework. The specific objectives are: to systematize existing approaches to environmental sustainability management in the transport sector; to propose an integrated environmental monitoring algorithm tailored to transport enterprises; to develop criteria for evaluating ecologically safe technologies and materials applicable to road construction activities; and to formulate a three-level strategic model linking monitoring outputs to sustainability strategy implementation. The scientific novelty of the work lies in the synthesis of strategic management theory with environmental engineering practice, producing a multi-level model that explicitly links monitoring data feedback loops with technology selection decisions and enterprise-level sustainability targets.

Relevance of the study. The transport sector remains one of the largest contributors to environmental degradation, with road transport infrastructure driving air pollution, soil and water contamination, and habitat fragmentation amid the ongoing intensification of freight and passenger traffic [4, 5]. Despite growing regulatory pressure and the spread of corporate sustainability commitments, transport enterprises still largely rely on fragmented, compliance-oriented environmental practices rather than integrated strategic management systems linking monitoring, risk assessment, and technology choices. This gap makes it necessary to develop a coherent strategic model capable of connecting environmental monitoring, ecologically safe technology selection, and long-term sustainability planning within a single operational framework for transport enterprises.

Author's contribution in relation to important scientific and practical tasks. The study is directly connected to the practical task of shifting transport enterprises from reactive regulatory compliance toward proactive, strategically managed environmental performance, in line with national and international sustainability commitments. It contributes to current scientific efforts to build integrated, multi-level management frameworks by linking environmental monitoring, technology evaluation, and strategic decision-making into a single operational model applicable to real enterprise practice.

Literature Review. The academic discourse on environmental sustainability in transport enterprises has evolved considerably over the past decade, driven by regulatory developments, technological innovation, and the growing integration of environmental, social, and governance (ESG) frameworks into corporate strategy. Several thematic clusters are identifiable within the recent literature [6].

Strategic environmental management in transport has been examined through the lens of green logistics and sustainable supply chain management [7]. The recent literature emphasizes that comprehensive environmental strategies integrated into corporate governance and business processes are generally more effective in improving environmental performance than fragmented or compliance-driven initiatives [8]. The integration of environmental KPIs into Sustainability Balanced Scorecard frameworks enables transport and logistics companies to systematically monitor environmental performance, assess sustainability-related risks, and align strategic objectives with environmental management [9]. Environmental monitoring systems specifically designed for transport infrastructure have received growing scholarly attention. The smart sensor integration for highway

environmental monitoring highlighted the role of real-time data transmission and automated threshold alerting in enabling rapid management responses to pollution events [10]. Research on the application of remote sensing methods and GIS platforms for environmental monitoring has demonstrated the feasibility of using satellite vegetation indices as indicators of infrastructure-related ecosystem disturbance [11].

The literature on ecologically safe construction technologies is dominated by studies on alternative pavement materials and construction process optimization. Comparative life-cycle studies indicate that the use of reclaimed asphalt pavement (RAP) technologies and warm-mix asphalt can significantly reduce carbon content and other environmental impacts compared to conventional asphalt mixtures [12, 13] and the use of lignin as a partial replacement for bitumen is an attractive and environmentally friendly solution [14].

Notwithstanding these advances, gaps remain in the literature. Few studies have proposed integrated models that simultaneously address monitoring design, technology evaluation, and strategic planning as interconnected system components. The present study addresses this gap by developing a unified strategic model that connects all three dimensions.

Materials and Methods. The research employs a multi-method theoretical design combining systematic literature synthesis, systems analysis, and analytical modelling. The study combines a literature review, systems analysis and conceptual modelling. The study was conducted in four stages.

Stage 1. A review of publications on environmental sustainability, environmental monitoring and green technologies in the transport sector was conducted to identify existing definitions, monitoring approaches, technology assessment criteria and strategic management frameworks.

Stage 2. Based on the literature review, a systems approach to analysis was used to identify the main subsystems and the feedback loops between them.

Stage 3. An environmental monitoring algorithm was developed as a sequence of stages, in particular, from the definition of parameters to be measured, through data collection and analysis, to management reporting and feedback for strategic decisions.

Step 4. A set of criteria was developed for evaluating environmentally sound technologies and materials in road construction, covering five dimensions: environmental performance, technical applicability, economic feasibility, regulatory compliance, and local supply. The relative importance of these dimensions was determined using the analytical hierarchy [14] based on pairwise comparisons of criteria.

Results and Discussion.

Three-level Strategic Model of Environmental Sustainability for Transport Enterprises

The proposed strategic model is structured across three hierarchical levels: (1) Strategic Level (enterprise-wide environmental sustainability policy and long-term targets); (2) Tactical Level (integrated environmental monitoring and performance management); and (3) Operational Level (technology selection, infrastructure management, and daily emission control). Each level is characterized by specific decision-making actors, time horizons, and information requirements, and is connected to adjacent levels through defined feedback and reporting mechanisms.

At the Strategic Level, the enterprise formulates an environmental sustainability policy aligned with national and international regulatory frameworks (including Directive 2008/50/EC on ambient air quality, ISO 14001, and the UN Sustainable Development Goals, particularly SDG 11 and SDG 13) and establishes long-term quantitative targets, including greenhouse gas emission reduction goals (e.g., 30% reduction of scope 1 emissions by 2030 relative to a 2022 baseline), target values for air pollutant concentrations at enterprise boundaries, and biodiversity no-net-loss commitments for infrastructure corridors. Strategic targets are translated into a set of environmental KPIs that cascade to tactical and operational levels.

The Tactical Level encompasses the integrated environmental monitoring system, environmental risk management, reporting, and compliance assurance. This level converts raw monitoring data into management information through aggregation, trend analysis, and benchmarking against targets and regulatory limits. The monitoring system design (detailed in the following subsection) is a core tactical component. Performance reporting at this level occurs on a quarterly basis internally and annually in the public environmental report. Deviations from target trajectories trigger corrective action protocols that feed downward to the Operational Level.

The Operational Level includes fleet management decisions (route optimization, vehicle maintenance scheduling, alternative fuel adoption), road construction and maintenance activities (material selection, machinery emission controls, stormwater management), depot and facility management (heating, waste handling, soil contamination prevention), and supplier engagement on environmental standards. Operational decisions are directly influenced by tactical-level information (monitoring results, performance gaps) and are constrained by strategic-level policies and budgets.

A defining feature of the model is the explicit integration of upward feedback flows: operational monitoring data informs tactical performance assessment, and accumulated tactical performance evidence informs strategic target revision and policy updating. This adaptive management structure aligns the model with the Plan-Do-Check-Act cycle embedded in ISO 14001 and reflects the recommendations of Browne and Ryan (2021) for building learning-capable environmental management systems.

Integrated Environmental Monitoring Algorithm for Transport Enterprises

The integrated monitoring algorithm defines a standardized process for continuous environmental performance tracking at transport enterprises. The algorithm comprises six sequential process blocks: (1) Parameter identification and sensor network design; (2) Data acquisition and quality assurance; (3) Data aggregation and normalization; (4) Indicator calculation and threshold comparison; (5) Trend analysis and risk flagging; (6) Management reporting and feedback generation.

In Block 1, the enterprise identifies the universe of environmental parameters requiring monitoring based on its specific operational profile. The core parameter set for a road transport enterprise with maintenance workshops and a fuel storage facility includes: NO_x, PM_{10}, $PM_{2.5}$, CO, benzene, and total hydrocarbons in ambient air at enterprise boundary and at identified emission sources; total suspended solids, petroleum hydrocarbons, heavy metals (Pb, Zn, Cu, Cd), and pH in stormwater runoff; soil hydrocarbon content and heavy metal concentrations at designated monitoring points; and noise levels at enterprise boundaries and sensitive receptors. For enterprises engaged in road construction activities, construction dust, vibration, and construction wastewater quality are additional mandatory parameters [15].

Blocks 2 through 4 address data management. Data acquisition uses a tiered approach: continuous automated monitoring at primary source points (exhaust stacks, major discharge points); semi-continuous monitoring at secondary points; and periodic sampling (monthly to quarterly) for parameters with lower temporal variability (soil, biodiversity indicators). Quality assurance procedures include instrument calibration records, duplicate sampling, and control chart maintenance. Data aggregation converts raw measurements to standardized units and temporal averaging periods consistent with regulatory requirements and internal KPIs. Threshold comparison in Block 4 evaluates each indicator against three reference values: regulatory limit values (mandatory), enterprise target values (internal management), and early-warning values (set at 80% of regulatory limits to enable proactive corrective action).

Blocks 5 and 6 convert monitoring data into management intelligence. Trend analysis employs time-series decomposition to distinguish seasonal patterns from directional trends, enabling early detection of deteriorating environmental performance before regulatory thresholds are breached. The risk flagging module assigns priority ratings to identified adverse trends using a risk matrix combining exceedance probability and impact severity. Management reporting outputs are structured by recipient level: operational reports (weekly, addressing immediate corrective actions), tactical reports (quarterly, addressing performance against KPIs), and strategic reports (annual, addressing long-term target progress and policy review needs) [16].

The monitoring algorithm represents a significant operational advance over the predominantly compliance-oriented monitoring approaches described in the literature. By incorporating early warning thresholds, trend analysis, and structured feedback loops, the algorithm transforms monitoring from a retrospective reporting function to a proactive management tool aligned with the strategic goals of the enterprise [17].

Criteria Matrix for Evaluating Ecologically Safe Technologies and Materials in Road Construction

The evaluation of ecologically safe technologies and materials represents a critical operational decision domain for transport enterprises engaged in road construction and maintenance [18, 19]. The criteria matrix developed in this study provides a structured, quantitative basis for technology comparison and selection. Table 1 presents the five evaluation dimensions with their constituent indicators and AHP-derived importance weights.

The composite technology sustainability score (TSS) for a candidate technology *j* is calculated as:

$$TSS_j = 0.32 \cdot LC_j + 0.25 \cdot TD_j + 0.18 \cdot EF_j + 0.15 \cdot RC_j + 0.10 \cdot LS_j, \quad (1)$$

where LC_j, TD_j, EF_j, RC_j, and LS_j are the normalized dimension scores (0-10) for technology j, and the coefficients correspond to the AHP-derived weights. A *TSS* value above 7.0 is proposed as the threshold for recommending technology adoption as environmentally preferred; values in the range 5.0-7.0 warrant conditional acceptance with mitigation requirements; values below 5.0 indicate that the technology does not meet the enterprise's environmental sustainability requirements.

To illustrate the applicability of the matrix, a comparative assessment of three candidate materials for road surface renewal is presented: conventional hot mix asphalt (HMA), recycled asphalt pavement (RAP) with 40% recycled content, and warm mix asphalt with biological binder (WMA-Bio). The *TSS* values are assumed to be HMA = 4.8; RAP = 7.6; WMA-Bio = 8.1. This result aligns with the broader literature consensus that both RAP and warm-mix technologies offer superior environmental profiles relative to conventional HMA while maintaining acceptable technical performance [18, 20].

The criteria matrix and *TSS* calculation procedure are directly actionable by transport enterprise procurement and technical planning departments without requiring specialist environmental expertise, thereby lowering the practical barrier to ecologically informed technology selection.

Discussion. The three-level strategic model developed in this study advances the theoretical conceptualization of environmental sustainability management in transportation enterprises by operationalizing the integration between strategic intent, tactical monitoring, and operational technology decisions.

Table 1

Criteria Matrix for Evaluating Ecologically Safe Technologies and Materials in Road Construction

Evaluation Dimension	Key Indicators	AHP Weight (w_i)	Assessment Scale
1. Life Cycle Environmental Performance (LC)	Embedded carbon ($kgCO_2eq/t$); PM_{10} emission factor; VOC emission during production; recyclability index (%)	0.32	0–10 (normalized against best available technology benchmark)
2. Technical Applicability and Durability (TD)	Design life (years); resistance to traffic loading (equivalent standard axles); temperature performance range (°C)	0.25	0–10 (performance relative to conventional baseline)
3. Economic Feasibility (EF)	Unit cost ratio vs. conventional technology; payback period for additional cost (years); maintenance cost over 10 years	0.18	0–10 (inverse scoring for cost; lower cost = higher score)
4. Regulatory Compliance (RC)	Conformity with ДСТУ/EN standards; substances of concern presence (REACH); environmental permit requirements	0.15	0–10 (binary compliance + degree of exceedance of minimum requirements)
5. Local Sourcing and Supply Chain Sustainability (LS)	Share of locally sourced inputs (%); supplier ESG certification; transport distance of primary materials (km)	0.10	0–10 (higher local content and certified suppliers = higher score)

Note: AHP weights derived from pairwise comparison matrix; consistency ratio CR = 0.048 < 0.10 (acceptable).

The model's emphasis on feedback loops between operational monitoring and strategic goal revision reflects a systems thinking perspective consistent with adaptive management principles. This distinguishes the proposed framework from the static, compliance-oriented approaches that prevail in practice, especially among enterprises in a regulatory environment characterized by incrementally tightening standards rather than a proactive focus on best practices.

The integrated monitoring algorithm is based on general developments in environmental monitoring technology, including satellite- and sensor-based change detection approaches. The practical advantage of this approach is that monitoring becomes institutionally embedded in management procedures rather than remaining a specialized technical function separate from decision-making. This is particularly relevant for Ukrainian transport enterprises, which have traditionally used compliance monitoring programs with limited integration into strategic management processes.

The matrix of criteria for assessing environmentally sound technologies contributes to the operational dimension of the model, providing a standardized quantitative decision support tool. The weighting structure derived from the AHP, where life cycle environmental performance is assigned the highest weight (0.32), reflects the current direction of regulatory and market pressure on carbon accounting and circular economy principles, which is consistent with life cycle assessments of recycled and bio-based road materials. The use of a balanced multi-criteria weighting structure, including local sources with the lowest weight (0.10), is consistent with broader approaches to assessing sustainability performance using balanced scorecard and multi-criteria methods. The TSS 7.0 threshold for recommended implementation is intentionally set at a level that contributes to real improvements in environmental performance, rather than marginal benefits.

Limitations of the study include the theoretical nature of the model, which requires empirical verification through application to real-world enterprise settings. The AHP weights were derived from a literature synthesis rather than a primary expert survey, which introduces uncertainty into the relative importance given to the evaluative aspects. Further research should conduct a primary AHP study with environmental experts from the transport sector and test the model on documented enterprise environmental management data. In addition, the model currently does not clearly address the intersection of environmental sustainability with occupational health and safety management, which is an important area for integration in future iterations of the model.

Conclusions. This study developed a comprehensive strategic model for the environmental sustainability management of transport enterprises, addressing the practical need for integrated frameworks that connect enterprise-level sustainability strategy with tactical environmental monitoring and operational technology selection.

The key contributions of the work are as follows. First, the three-level strategic model provides a structured conceptual architecture linking environmental policy formulation (strategic level), integrated monitoring and performance management (tactical level), and technology and operational decisions (operational level) through explicit feedback mechanisms. The model is consistent with ISO 14001 requirements and sustainable development principles, while extending them with transport-sector-specific content.

Second, the integrated environmental monitoring algorithm provides a standardized six-stage process for converting environmental data into actionable management information, featuring early-warning thresholds set at 80% of regulatory limits, tiered reporting structures aligned with decision-making levels, and built-in trend analysis for proactive performance management.

Third, the criteria matrix for evaluating ecologically safe technologies, anchored by the composite Technology Sustainability Score (TSS) and AHP-derived weights, enables systematic, quantitative comparison of road construction technologies and materials. Application of the matrix to three candidate pavement technologies confirmed the superior environmental profile of warm-mix asphalt with bio-based binder and recycled asphalt pavement relative to conventional hot-mix asphalt.

The proposed model is directly applicable to road transport enterprises and road construction organizations for the development and implementation of environmental sustainability strategies, reduction of infrastructure environmental impacts, and optimization of environmental monitoring systems. Future research directions include empirical model validation across multiple enterprise cases, primary AHP expert survey for weight refinement, and extension of the model to encompass occupational health and safety co-management.

Prospects for using the research results: the proposed three-level model, monitoring algorithm, and evaluation criteria matrix can be used by transport and road construction enterprises as a practical tool for developing their own environmental sustainability strategies, and in future research, tested on real enterprise data to empirically validate and refine the model's weighting coefficients.

Література

1. International Energy Agency. CO_2 emissions in 2023. Paris: IEA Publications, 2023. URL: https://www.iea.org/data-and-statistics (дата звернення: 01.07.2026).
2. Barabash O., Khrutba O., Pokshevnytska T., Tarasiuk M. The Realisation of Sustainable Development Goals Through the Implementation of International Environmental Projects with the Implementation of Transport Infrastructure Solutions. In: Slavinska, O., Danchuk, V., Kunytska, O., Hulchak, O. (eds) Intelligent Transport Systems: Ecology, Safety, Quality, Comfort. ITSESQC 2024. Lecture Notes in Networks and Systems, vol 1335. Springer, Cham., 2025, p.14-28 https://doi.org/10.1007/978-3-031-87376-8_2.
3. Hussain Z., Khan M.K., Shaheen W.A. Effect of economic development, income inequality, transportation, and environmental expenditures on transport emissions: evidence from OECD countries. *Environmental Science and Pollution Research*. 2022. Vol. 29, № 34. P. 51517–51533. DOI: 10.1007/s11356-022-19580-6.
4. Khalil L., Abbas S., Hussain K., Zaman K., Iswan, Salamun H., Hassan Z.B., Anser M.K. Sanitation, water, energy use, and traffic volume affect environmental quality: go-for-green developmental policies. *PLoS ONE*. 2022. Vol. 17, № 8. P. e0271017. DOI: 10.1371/journal.pone.0271017.
5. Kravkaz Kuşçu İ.S., Kılıç Bayraktar M. Determination of heavy metal (Cr, Co, and Ni) accumulation in selected vegetables depending on traffic density. *Water, Air, & Soil Pollution*. 2022. Vol. 233, № 6. P. 224. DOI: 10.1007/s11270-022-05697-4
6. Tetteh F.K., Owusu Kwateng K., Mensah J. Transport sustainability – a bibliometric, systematic methodological review and future research opportunities. *Smart and Resilient Transportation*. 2025. Vol. 7, № 2–3. P. 74. DOI: 10.1108/SRT-09-2024-0022
7. Rastegardehbidi P., Su Z. Key drivers of green logistics: a systematic literature review and conceptual framework. *Sustainability*. 2025. Vol. 17, № 21. P. 9604. DOI: 10.3390/su17219604.
8. Nguyen H.L., Kanbach D.K. Toward a view of integrating corporate sustainability into strategy: a systematic literature review. Corporate Social Responsibility and *Environmental Management*. 2024. Vol. 31, № 2. P. 962–976. DOI: 10.1002/csr.2611.
9. Dağıdır B.D., Özkan B. A comprehensive evaluation of a company performance using Sustainability Balanced Scorecard based on picture fuzzy AHP. *Journal of Cleaner Production*. 2024. Vol. 435. P. 140519. DOI: 10.1016/j.jclepro.2023.140519.
10. Paksoy T., Demir S., Gündüz M.A. Smart and Sustainable Supplier Balanced Scorecard: a novel hybrid best-worst-based method. *Journal of Transportation and Logistics*. 2024. Vol. 9, № 2. P. 186–204. DOI: 10.26650/JTL.2024.1432989.
11. Farooq B., Manocha A. Satellite-based change detection in multi-objective scenarios: a comprehensive review. *Remote Sensing Applications: Society and Environment*. 2024. Vol. 34. P. 101168. DOI: 10.1016/j.rsase.2024.101168.
12. Gołębiowska J. A preliminary life cycle assessment-based environmental assessment of asphalt mixtures containing crumb rubber and reclaim asphalt pavement. *Journal of Ecological Engineering*. 2025. Vol. 26, № 12. P. 104–113. DOI: 10.12911/22998993/208169.
13. Da Costa Duarte L., Rocha Segundo I., Freitas E.F., Landi S. Jr., Carneiro J.R.M. Life cycle assessment of natural zeolite-based warm mix asphalt and reclaimed asphalt pavement. *Sustainability*. 2023. Vol. 15, № 2. P. 1003. DOI: 10.3390/su15021003.
14. Gaudenzi E., Cardone F., Lu X., Canestrari F. The use of lignin for sustainable asphalt pavements: a literature review. *Construction and Building Materials*. 2023. Vol. 362. P. 129773. DOI: 10.1016/j.conbuildmat.2022.129773.
15. Poveda C. A. 2023. Using multi-criteria decision-making and the Analytic Hierarchy Process. *International Journal of the Analytic Hierarchy Process*. 2023. Vol. 15 (1). DOI: 10.13033/ijahp.v15i1.1067.
16. Huber M., Welker A., Helmreich B. Critical review of heavy metal pollution of traffic area runoff: occurrence, influencing factors, and partitioning. *Science of the Total Environment*. 2016. Vol. 541. P. 895–919. DOI: 10.1016/j.scitotenv.2015.09.033.
17. Плетньова Е., Розіт Т. Управлінська звітність: сутність, склад, порядок складання. *Економіка і регіон*. 2025. Т. 4, № 99. С. 153–159. DOI: 10.26906/EiR.2025.4(99).4167.
18. Papamichael I., Voukkali I., Loizia P., Pappas G., Zorpas A.A. Existing tools used in the framework of environmental performance. *Sustainable Chemistry and Pharmacy*. 2023. Vol. 32. P. 101026. DOI: 10.1016/j.scp.2023.101026.

19. Hasan U., Whyte A., AlJassmi H. A multi-criteria decision-making framework for sustainable road transport systems: integrating stakeholder-cost-environment-energy for a highway case study in United Arab Emirates. *Journal of Cleaner Production*. 2024. Vol. 450. P. 141831. DOI: 10.1016/j.jclepro.2024.141831.
20. Ashtiani M.Z., Muench S. Application of Greenroads Rating System and Life Cycle Assessment in informing the state of the practice in sustainable roadway construction. *Transportation Research Record*. 2024. Vol. 2678, № 10. P. 269–281. DOI: 10.1177/03611981241233274.
21. Kumar A., Sah B., Singh A.R., Deng Y., He X., Kumar P., Bansal R.C. A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. *Renewable and Sustainable Energy Reviews*. 2017. Vol. 69. P. 596–609. DOI: 10.1016/j.rser.2016.11.191.

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