

Article

Advancing Sustainable Construction Through 5D Digital EIA and Ecosystem Restoration

Tomo Cerovšek

Faculty of Civil and Geodetic Engineering, University of Ljubljana, Jamova cesta 2, 1000 Ljubljana, Slovenia; tomo.cerovsek@fgg.uni-lj.si; Tel.: +386-1-4768-521

Abstract

The construction sector drives nearly half of global material extraction, energy use, emissions, and waste, yet environmental impact assessment (EIA) remains a static document, fragmented and disconnected from dynamic ecological systems. Here, we propose an upgrade to a five-dimensional (5D) EIA framework that integrates space-time analysis (3D + time = 4D) with real-time monitoring and impact quantification (5D) to account for environmental footprint and prevent irreversible impacts. The methodology included an analysis of over 100 EIA permits and reports, supplemented by interviews, reviews of technologies and process and systems analysis. Central to this approach is the inclusion of 4D building information models (BIM) and nature's self-cleansing capacity, which is often overlooked in conventional assessments. The proposed Integrated Environmental Decision Support Information System (I-EDSIS) would enable continuous impact tracking, cumulative effect evaluation, and insights into patterns for adaptive mitigation. Drawing on a national-scale case study, we show that building permits correlate with NO_x and PM_{10} ($r = 0.96$), while pollutant levels vary by up to 1.5–3 times across months and within a day, revealing potential for time-sensitive adaptive construction and less ecological disruption. This perspective argues for reframing EIA as a proactive tool for sustainability, transparency, active durability, cross-sectoral data integration, and resilience-based development.

Keywords: environmental impact assessment; environmental construction management; nature self-cleansing; BIM; lifecycle; 5D material flow; sustainability; eco-innovation



Academic Editor: Antonio Caggiano

Received: 11 August 2025

Revised: 18 September 2025

Accepted: 8 October 2025

Published: 13 October 2025

Citation: Cerovšek, T. Advancing Sustainable Construction Through 5D Digital EIA and Ecosystem Restoration. *Sustainability* **2025**, *17*, 9062. <https://doi.org/10.3390/su17209062>

Copyright: © 2025 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Manufacturing, logistics, supply chains, machinery, construction, operation and use of facilities cause noise, vibration, pollution, waste, and natural resource depletion and can affect the landscape, biodiversity, and land use (Figure 1). What is the extent of these impacts, and what are the key legal and natural mechanisms that mitigate them?

1.1. The Multifaceted Environmental Burden of Construction

Construction is cumulatively responsible for roughly 50% of air, 30% of water, and 50% of soil pollution; consumes 50% of natural resources [1]; and produces 35% of all solid waste [1]. In Luxembourg [2] and the UAE, 75% of solid waste stems from construction and demolition waste (CDW). Air, water, and soil pollution are often linked, e.g., rain washes airborne toxic particulate matter (PM) from the atmosphere into the soil, from which it can then leach into waterways. These particles may contain toxic substances that can harm people's health and the environment [3]. The World Health Organization (WHO) estimates that around 7 million people die yearly from exposure to fine particles [4]. The combustion

in manufacturing and construction alone causes 16% of PM_{10} and 27% of $PM_{2.5}$ particles [5] (PM sizes of 10 and 2.5 μm , respectively). Construction may double the PM concentration, which is especially critical in downwind areas [6].

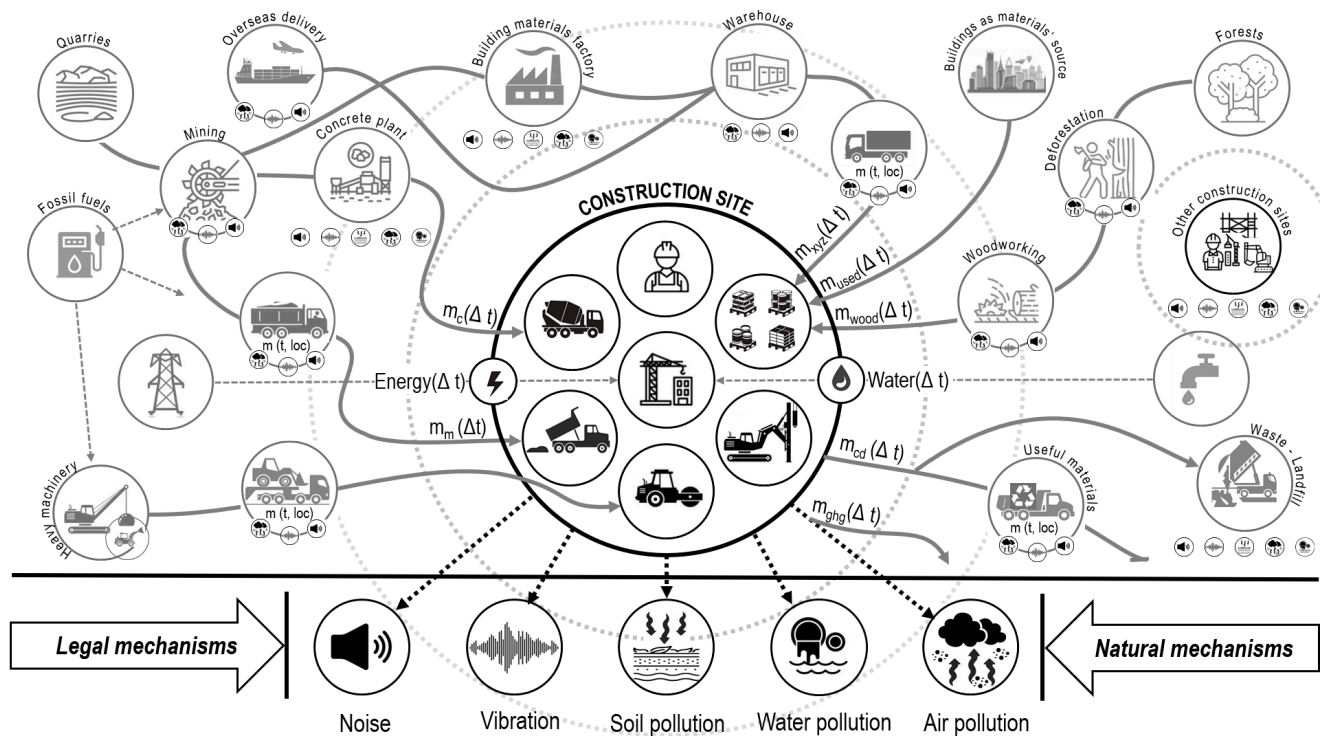


Figure 1. The environmental footprint of construction mitigated by legal and natural mechanisms. Dashed circle lines indicate broader impacts extending beyond the immediate project boundaries, dashed straight-line arrows indicate indirect relationships, while the bold arrows are direct ones.

The emissions, pollution, and waste in construction stem from immense amounts of processed raw and building materials. The extensive network of material sources and destinations highlights the scale of these material processes. Nearly 84 Gigatons of materials was extracted globally in a year—and only about 12% of materials are currently recycled [7], as waste streams mostly lead to landfills. The extraction of raw materials is expected to double by 2060, reaching a staggering 167 Gigatons [7]. Raw materials critical for construction, such as sand, gravel, crushed stone, and limestone, will increase the most, and these materials cause 98% of construction pollution [8]. In this context, the GHG protocol [9] will become an increasingly important tool for controlling emissions. Population and GDP growth are expected to increase construction activities [10]. Since both construction and building operations can cause irreversible environmental damage, stricter legal and regulatory controls over pollution and energy use are essential.

1.2. Legal Mechanisms: Environmental Impact Assessment (EIA)

In recent decades, environmental impact assessment (EIA) has evolved in the USA [11], EU [12], and worldwide into a key, legally binding tool for communication, collaboration, and decision making on environmental issues for construction projects and facilities that may have significant environmental impact.

The goal of EIA is to prevent irreversible processes and to minimize the negative impacts of human activities on communities and natural and built environments. EIA forces project developers to analyze, predict, consult, and discuss environmental issues and options before decisions are made and work is permitted. EIA also forces contractors to adapt their work, to monitor environmental indicators, and to report. EIA is evolving along

with supporting policies for environmental protection, e.g., capacity building, more inclusive processes, enhanced transparency, progress monitoring, and comparability. Table 1 provides an overview of the EIA stages [13] and the evolution of digitalization [14].

Table 1. An input–process–output (IPO) overview of EIA and advancements in its digitalization.

EIA Stage	Screening	Scoping	Preparation	Consultation	Decision Making	Monitoring
Input	Project details	Request on scope	Project information	EIA Report	Final EIA Report	Conditions on site
Process	Developer submits project details; the competent authority screens the information.	Developer may request opinion from competent authority on scope of the assessment.	Developer and consultants assess impacts and compile the EIA report.	Competent authority shares with stakeholders and the public for participation.	Competent authority examines the EIA report to issue a project decision.	Developer monitors effects and mitigation measures.
Output	Screening decision on whether the EIA is required for the project.	Scoping opinion on the required extent and content of the EIA.	EIA report with baseline, impacts, options, and mitigation efforts.	Feedback and comments from authorities/public and NGOs.	Reasoned conclusions and development consent (if permit is positive).	Monitoring reports and evidence of mitigation effects.
Advances in Digital EIA	Platforms for the digital notification and early access to project data with spatial analysis (env. GIS layers).	Digital portals for the stakeholders; interactive maps and data repositories assist in defining relevant impacts.	Digital models (e.g., BIM and GIS), environmental simulation tools, and cloud-based collaboration.	Platforms for EIA docs. Digital feedback tools and visualizations for understanding and participation.	Digital systems for review and archive reasoning for decisions. Some jurisdictions may use AI.	IoT sensors and digital dashboards for real-time env. monitoring and GIS. Platforms to track compliance/trend.

Beyond the formal EIA, understanding natural self-cleansing processes provides critical insights into the mechanisms by which ecosystems respond to environmental changes.

1.3. Natural Mechanisms: Natural Self-Cleansing

Natural self-cleansing may activate at different times and scales but depends on local conditions, as in the case of PM. The scale and effectiveness of natural self-cleansing processes vary enormously across different environmental contexts.

A fast-flowing river, for example, can effectively purify itself of biodegradable organic waste over a scale of several kilometers through dilution, microbial decomposition, and oxygenation. In contrast, ecosystems like the global atmosphere or deep oceans operate on a planetary scale, relying on vast dilution and much slower chemical and biological processes to mitigate widespread pollutants, such as greenhouse gases or persistent chemicals, over timescales of decades to millennia.

During the downscaling of human activities during the COVID-19 pandemic, remarkable evidence of nature’s self-cleansing was recorded at large scales from the space, air, surface, and subsurface of the Earth. Space satellite imagery showed that nitrogen dioxide plummeted in two months [15]; smog vanished from megacities [16,17]; PM₁₀, SO₂, and NO₂ were reduced by 50% [18]; waterfronts became clear; and river concentrations of Al, As, Ba, Cr, Ni, and Zn were reduced by over 30% [19].

Currently employed environmental protection measures often overlook the role of the natural self-cleansing and resilience capacities of ecosystems. This facet leads to conservative thresholds or mitigation measures that may not align with ecological dynamics or support regenerative outcomes. Integrating data on natural self-cleansing capacities into project planning and execution models enable optimized scheduling of construction activities, leading to a significant reduction in environmental disturbances and leveraging natural recovery cycles.

Table 2 provides questions that expose the importance of natural self-cleansing processes for sustainable construction, their consideration in the EIA, and the need for monitoring.

Table 2. The role of natural self-cleansing and the importance of monitoring to reduce the burden.

Domain	Question	Why It Is Critical for EIA	Why Better Monitoring Is Required
Noise	Has the ambient noise level recovered after previous phases to permit new noisy operations?	Prevents overlapping noise disturbances and respects rest cycles for humans and fauna.	Natural acoustic background levels change seasonally and with vegetation regrowth.
Vibration	Are sensitive structures or geological formations still absorbing shock, or has the stress dissipated?	Protects structural integrity and prevents cumulative fatigue and slope destabilization.	Subsurface recovery depends on ground composition and time since the last vibration needs sensors.
Air	Will today's wind, humidity, and pollutant concentrations allow safe dispersion of dust, PM and NO _x ?	Prevents unnecessary exceedances and reduces health impacts through predictive scheduling.	Depends on atmospheric self-cleansing (dispersion and deposition) that is not visible.
Water	How long after sediment release will turbidity and nutrient levels return to baseline in downstream habitats?	Prevents overlapping discharges, protects fish spawning, and aligns with eventual permit compliance.	Recovery windows depend on flow, sedimentation rates, and biological uptake; dynamic and site-specific.
Soil	Has microbial or vegetative regeneration sufficiently reduced to support further work?	Avoids ecosystem disruption and ensures soil productivity is not undermined.	Natural recovery is nonlinearly influenced by different factors, and it requires temporal tracking.
Waste	Can deconstruction and waste reuse be optimized by aligning demolition with resource recovery capacity?	Minimizes landfill use and promotes circularity.	Requires integrated material flow data and real-time logistics and awareness of the activities in the surrounding areas.
Biodiversity	Has species richness or key indicator populations recovered enough post-disturbance to resume high-impact work nearby?	Prevents biodiversity loss and legal infractions (e.g., during breeding/migration).	Recovery monitoring (e.g., camera machine vision and acoustic sensors) is needed to assess readiness, not assumptions.
Cumulative Impact	Are we initiating work in a basin that has not yet recovered from previous overlapping construction activities?	Avoids regional overload and ecosystem tipping points.	Time-series integration of stressors and recovery patterns can reveal environmental debt or resilience.
Decision Timing	Can we accelerate or delay demolition based on forecasted rain or wind?	Optimizes interventions in sync with natural buffers and reduces risks.	Requires real-time data integration and simulation of what-if scenarios.

1.4. Contributions of This Study

This work responds to pressing gaps in current environmental assessment practices by developing a multidimensional approach that integrates digitalization, monitoring, and governance. Its unique contributions can be summarized as follows:

- Integration of BIM and EIA through a 5D framework, combining 4D modeling with real-time environmental monitoring and adaptive scheduling.
- Inclusion of natural self-cleansing processes as a systematic component of evaluation, ensuring that human interventions and ecosystem capacities are recognized in EIA.
- Development of the I-EDSIS framework, a governance-oriented system for continuous monitoring;
- Cumulative environmental control that strengthens decision making across project and regional scales.
- Empirical grounding of the framework through analysis of national pollution datasets and expert interviews, directly linking data-driven insights to construction.

Together, these contributions highlight the shortcomings of current EIA practices, identify opportunities for improvement, and demonstrate a multidimensional framework that supports more sustainable, adaptive construction. The following section outlines the research methods employed to develop and test this approach.

2. Research Methods

Outlined shortcomings were selectively investigated by reviewing existing practices via unstructured interviews, literature surveys, and systemic and process analyses. A circular representation of the research methods (Figure 2) highlights the iterative and interactive nature of the research design and its implementation. Particular research methods depicted in the middle ring were not executed sequentially but, instead, applied interchangeably in response to findings and evolving research needs.

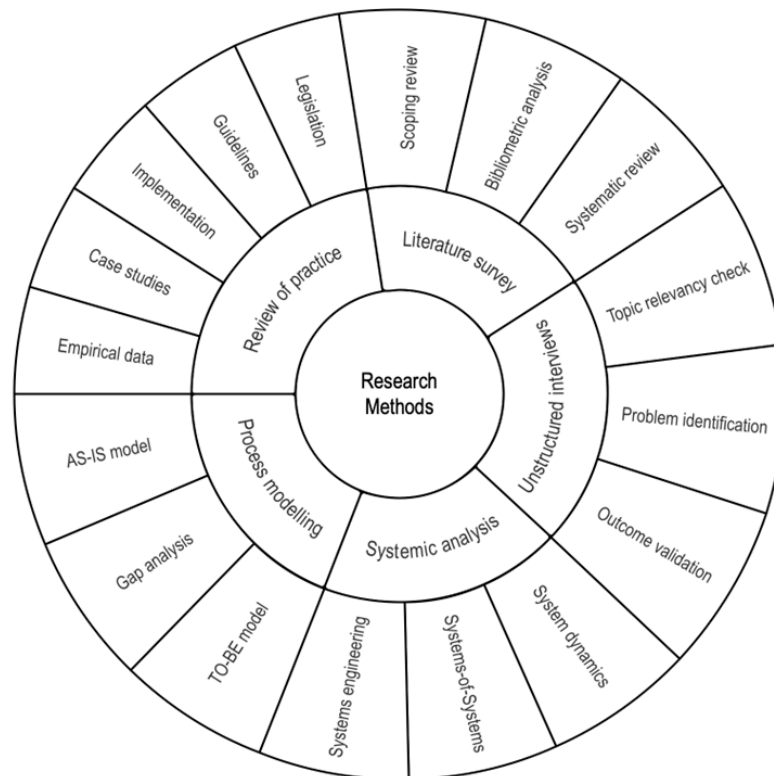


Figure 2. The research methods used for the environmental study.

This section provides a brief overview of the foundational research methods employed in this study, namely, a review of practices, a literature survey, and unstructured interviews. The subsequent section builds upon this foundation, detailing the process modeling and systemic analysis undertaken. These analytical phases form the basis for the proposed comprehensive system framework.

2.1. Literature Survey

The literature review employed multi-faceted reviews. A scoping literature review mapped the existing body of research and identified key gaps. This guided follow-up systematic reviews to address the most critical underexplored aspects.

Keywords (Appendix B.1) were refined iteratively for the bibliometric analysis, which identified active research fields, key authors, leading institutions, and relevant sources. The outcome of the scoping review and bibliometric analysis was used to identify the most active research fields in the domain, influential authors, leading institutions, and, importantly, the most relevant primary and secondary sources of information.

Essential primary sources included top scientific publishers, reports from the Organisation for Economic Co-operation and Development (OECD), the European Environment Agency (EEA), and the US Environmental Protection Agency (US EPA). The two main secondary sources used for discovery were Scopus and Google Scholar. Table 3 provides a

high-level overview of the scoping literature review process, drawing on selected primary and secondary sources, along with a basic bibliometric analysis.

Table 3. Quantitative literature review: the number of papers on key EIA stages (Appendix B.1).

Source	Screening	Scoping	Preparation	Consultation	Decision Making	Monitoring
Scopus	122	83	201	271	185	1560
Scholar	3030	6380	5740	4840	3060	6190
OECD	287	706	468	351	276	813
EU EEA	285	708	2111	943	394	2286
US EPA	4188	3547	9281	4242	4445	5031

The initial scoping and bibliometric analysis were based on the keywords that represent all major steps of the environmental impact assessment (EIA) process, enabling a targeted search. The search strategy was adapted for use in different databases, as specified in Appendix B.1. For instance, Scopus and Google Scholar are limited to either a broad full-text search or a narrow title-only search. While the full-text search was useful for identifying the breadth of the research works, the title-only search helped pinpoint highly focused studies. The insights from these initial stages of scoping the literature review and bibliometric analysis then guided a systematic review of the related work, presented here, and the literature presented in the follow-up sections.

Digital twin research has produced notable advances across different environmental domains. Studies on digital twins in the domain of air quality for real-time urban monitoring and the simulation of intervention impacts highlight challenges of data quality, model scalability, and adaptation to local contexts [20]. The strongest gains have been reported in water management. Digital twins for water management have demonstrated high-accuracy predictions of water contamination [21], as well as advantages for real-time feedback loops and policy optimization [22]. Additionally, they enable the integration of high-resolution monitoring, real-time water quality assessments, and predictive simulations [23]. In comparison, studies on digital twins for soil contamination and ecosystem restoration are more conceptual, e.g., frameworks linking soil microbiota with ecosystem services [24], integration principles for soil health monitoring [25], and potential for estimates of degradation rate and automation in real-time monitoring [26], but quantitative outcomes are rarely reported. Across domains of air, water, and soil, as well as climate studies [27], digital twins yield the most tangible advances in water management, particularly in real-time monitoring, predictive modeling, and decision support.

Recent research on urban metabolism complements presented studies by integrating material and energy flow analysis with life cycle assessment [28], enabling both retrospective evaluations and scenario-based assessments of circular strategies across sectors and regions. Coupled digital twins, BIM, and system dynamics were suggested to represent spatially explicit resource flows in urban metabolism at multiple scales [29]. Other studies focusing on megacities employ multi-criteria decision tools with GIS to map sustainability and resilience indicators [30,31]. Meanwhile, holistic frameworks emphasize the combination of material flow analysis, governance mechanisms, and stakeholder co-creation in guiding urban design and relevant policies [32]. Within the construction sector specifically, strategies emphasizing material reduction have shown greater benefits than recycling alone, and spatially explicit analyses reveal burden-shifting patterns that underscore the need for tailored circular economy interventions [28].

Recent studies on circular construction link core principles to sustainable development and CDW minimization through multi-criteria models that integrate stakeholder engagement, life cycle thinking, and cost-benefit assessments [33]. Some studies highlight common strategies such as reducing, reusing, recycling, recovering, and upcycling, while

others describe tools and methodologies, such as Life Cycle Assessment and Interpretive Structural Modeling, which enable an evaluation of environmental performance [34]. Digital and technological innovations receive growing attention [35], with pilots involving BIM, blockchain, material passports, and computational assessment. Policy and regulatory studies, however, reveal fragmented approaches that still favor recycling over reuse due to institutional, technological, and organizational challenges [36]. The review suggests that circular economy frameworks in CDW management are still in an early stage, with a shift toward integrated and adaptive approaches [33].

Despite these advances, current approaches remain fragmented with partial focus. This separation leaves gaps in governance integration, environmental assessment by design, and the explicit consideration of natural self-cleansing capacities, as well as in adaptive decision making across scales. This fragmentation underscores the need for a unifying framework. Identified gaps and related issues also provided initial input for unstructured interviews and for the review of current practices.

2.2. Unstructured Interviews

To ensure practical applicability, the study prioritized depth of inquiry over quantitative breadth. Rather than conducting a large survey, a targeted series of eight unstructured expert interviews was carried out. These dialogues confirmed the relevance, clarified research problems, and preliminarily validated the outcomes. Eight experts were interviewed with guiding questions that evolved iteratively. Questions targeted gaps in environmental integration, including early stakeholder involvement, limited impact data, weak modeling, low technology adoption, poor transparency, monitoring issues, rigid regulations, limited post-project learning, and inadequate simulation tools. Responses were thematically coded and synthesized around recurring issues, including cumulative impacts, monitoring gaps, stakeholder engagement, and regulatory enforcement. Each expert addressed only those aspects most pertinent to their role, resulting in nuanced and concentrated contributions that complemented the literature review and practice analysis.

The guiding questions focused on key gaps in environmental integration for major infrastructure projects, including:

- *Process*: Underutilization of EIA in design processes, lack of material flow modeling, Inflexible regulatory procedures, Insufficient post-project learning with no feedback.
- *Information*: Limited cumulative impact data, Need for integration of data for sustainable project, environmental awareness, project planning, execution and controlling.
- *Stakeholders*: Early stakeholder involvement, poor transparency for key opponents of the projects, limited public engagement, lack of personnel for governmental control.
- *Technology*: Lack of equipment to allow for monitoring on a project level and lack of adoption of novel technologies, Contractor monitoring limitations.

The full list of profiles and questions is available in Appendix B.3.

2.3. Review of Practice

The review of practice began with a comprehensive analysis of environmental legislation and guidelines from the European Union (EU), the United States (US), the United Kingdom (UK), and relevant local jurisdictions. During this process, these frameworks were systematically screened to identify provisions related to the use of digital technologies. The screening aimed to map the current legal landscape and determine how existing regulations address, encourage, or mandate the application of digital tools for environmental monitoring, reporting, and compliance. A review of environmental legislation was undertaken as the initial phase of the overall review of practice. During this process, relevant directives were systematically screened to identify provisions related to the use

of digital technologies. The screening process aimed to map the current legal landscape and determine how existing regulations address, encourage, or mandate the application of digital tools for environmental monitoring, reporting, and compliance.

Projects reviewed (see sources: Appendix B.2) included a variety of buildings (residential complexes, logistics centers, industrial plants) and infrastructure (roads, bridges, railways, pipelines, renewable energy plants, quarries, and water treatment facilities).

The research revealed that current environmental procedures underuse existing digital technologies, which could improve insight into impacts from material and energy flows and their mitigation through human and natural processes. To address this challenge, our study will employ detailed process modelling and systemic analysis.

3. Process Analysis

Building on EIA's role in mitigating construction impacts, we examine its underlying processes. To illustrate how EIA functions and how proposed solutions may improve it, we use a standardized process-mapping method known as IDEF0. This method breaks down systems into activities, their inputs, outputs, controls, and resources and mechanisms, making interdependencies and connections easier to understand.

In the following sections, we complete re-engineering in three steps:

- Section 3.1 maps the “As-Is” (current state) of EIA practices in construction;
- Section 3.2 identifies inefficiencies and gaps;
- Section 4 introduces the “To-Be” (future state) process model.

3.1. AS-IS Process Model of EIA

The context diagram in Figure 3, further broken down in Figure 4, allows us to pinpoint inefficiencies and gaps.

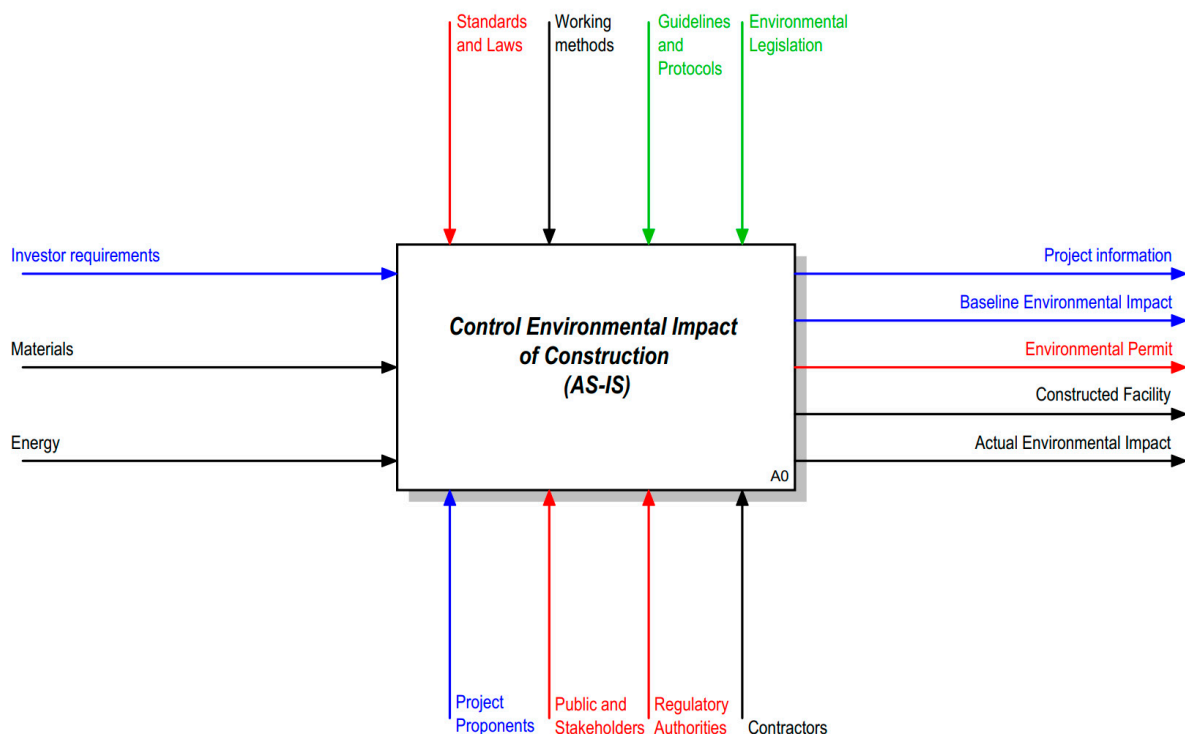


Figure 3. The As-Is EIA process context of the control of environmental impacts (excl. screening and scoping), with main inputs (left), controls (top), outputs (right), and mechanisms (bottom). Blue denotes project development information, red denotes permitting and inspection, black denotes on-site material and energy flows, and green are flows related to greening and sustainability.

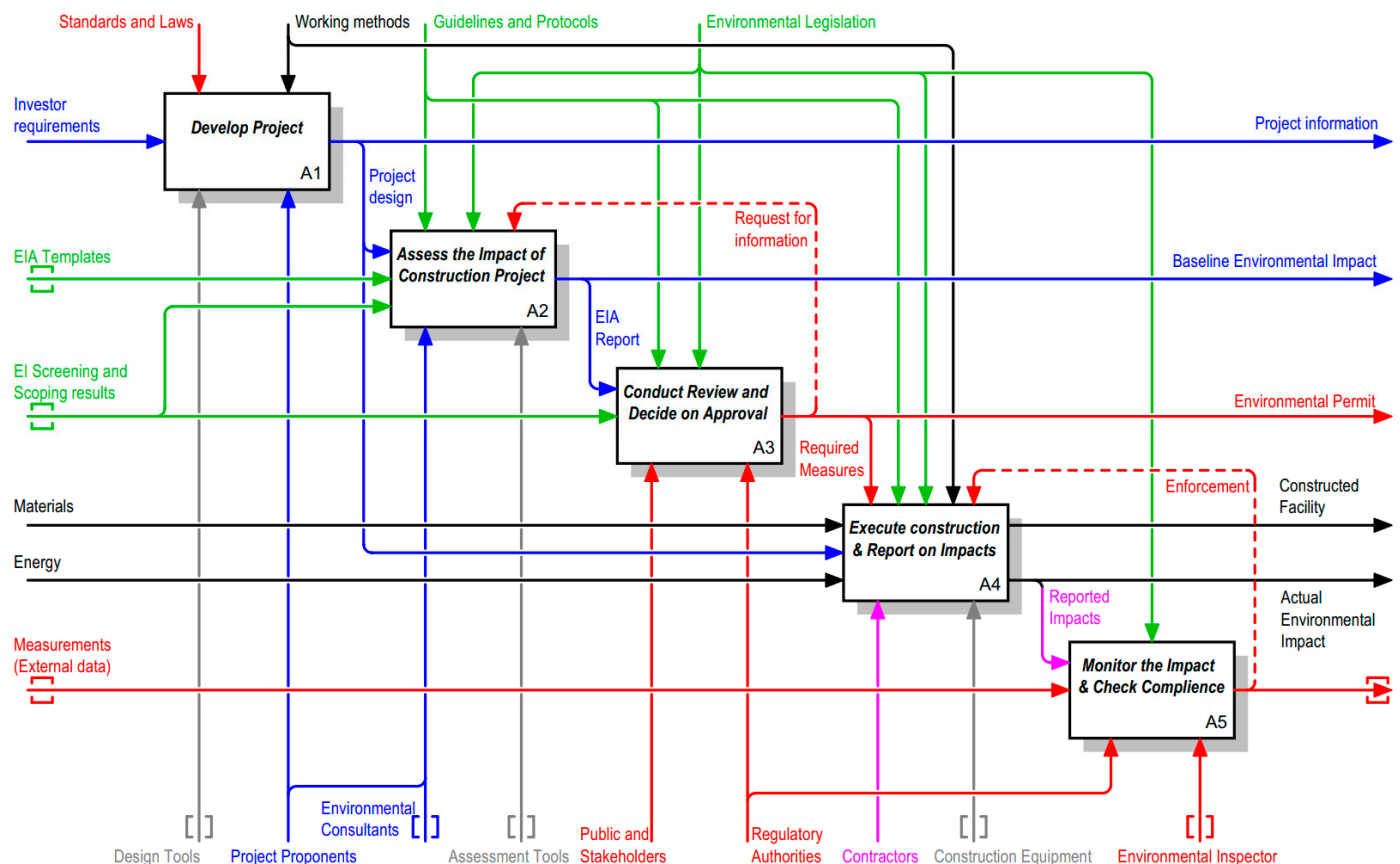


Figure 4. The simplified As-Is EIA of current practices of controlling environmental impacts in the context of project development. Blue denotes project development information flows, red denotes permitting and inspection flows, black denotes on-site material and energy flows, green denotes flows related to greening and sustainability, and dashed lines represent optional flows.

This process focuses on the EIA start with screening [37] and scoping [13] phases. Inputs include initial project data, investor requirements, materials and energy. Controls are common standards and laws, guidelines, working methods and environmental legislation. Outputs include environmental permits and impact assessments. Mechanisms involve project proponents, public and other stakeholders, regulatory authorities, and contractors, each with distinct views and responsibilities. Figure 4 is a simplified As-Is representation of current practices in the environmental oversight of construction projects.

During construction, contractors use construction equipment, and they may also implement an environmental management system (EMS). Large and small firms may differ in EMS usage, with some adopting standalone project-specific EMSs (e.g., for environmental standards) and others using integrated systems (IMSS) for efficiency. Customized or hybrid EMSs are common and may provide EIA follow-up compliance reporting.

3.2. EIA Gap Analysis

Table 4 provides an overview of identified gaps in EIA. EIA reports are based on static preconstruction projections, with little integration of real-time data once projects begin. This leads to delayed responses, passive mitigation, and limited adaptation by construction professionals. This disconnect results in delayed responses to risks and in passive mitigation strategies and does not motivate construction professionals to adapt their ongoing activities. EIA often underestimates cumulative effects and interactions among projects, leading to higher overall impacts than individual studies suggest.

Table 4. Gap analysis in the As-Is process model of environmental impact control.

Process Activity	Process Gaps	Input–Control–Output–Mechanism (ICOM) Gaps
Develop project, design, and plan	Lack of interdisciplinary collaboration and early involvement of all relevant stakeholders [38] Lack of mitigation measures by design [39] Limited availability and accuracy of environmental information [40] and cumulative IA [41,42] EIA not used by design; the focus is on the reduction in the impact of fixed solutions No account of novel technologies that can better control the material flow and use of resources	I: Limited information on materials, waste, and other relevant baseline environmental information [43] C: Control of impact using cumulative effects to be used as integral part of the design O: Lack of information with integrated 4D/5D models, enabling simulation of a complete material flow M: Lack of design assessment tools integrated with environmental system with available accurate data
Assess the impact of the construction project	Limited availability of information and scope Difficult consideration of variable conditions [44] Inconsistent information, standards, and regulations Not considered dynamic in construction projects Not considered variable and unpredictable natural conditions, resilience, and connectivity [45] Rigid and unresponsive regulatory approaches	I: Project documentation at various design stages/project phases C: Lack of standardized methods and rules for calculations; evolving legislative requirements O: Baseline environmental impact relative to the reference material flow (4D) and natural conditions M: Integrated environmental system with sources
Share, comment, and examine the EIA report	Limited public awareness and time availability Limited project understanding/interpretation Lack of transparency and streamlined interactions [46,47] Limited access to the project documentation Lack of presentations for the general public; Aarhus convention requirements not met [46]	I: Lack of presentations for the general public Lack of regular updates through the project lifecycle [47] C: Lack of management of stakeholders [48] O: Lack of feedback with sufficient technical information M: Lack of simulations for the general public; lack of communication channels
Execute construction project and report	Lack of contractor expertise and time constraints Demanding data management and reporting Lack of assessment of cumulative effects [42] Lack of long-term requirements for monitoring Reporting and mitigation in construction phase [49]	I: Contracts can include requirements on EI, questionable financing of monitoring [47] C: No requirement to report and document compliance to the consent O: Lack of information on natural cleansing M: Lack of equipment for monitoring local conditions, lack of automated reporting mechanisms
Monitor the impact of construction projects	Lack of monitoring and auditing [46] Limited enforcement of environmental permits [46] Insufficient consideration of cumulative effects Inadequate support for real-time monitoring and/or insufficient availability of monitoring data [50] Complexity of management of technology Overemphasis on environmental parameter peaks Lack of overall post-EIA follow up/feedback [51,52]	I: Real-time relevant sample data are not available and data on used materials/equipment are missing C: Insufficient enforcement of environmental permits and lack of appropriate monitoring guidelines [47] O: Actual material fluxes are not recorded, no feedback to learn from past projects [47], and limited information on actual environmental outcomes [53] M: Lack of personnel with appropriate training; lack of specialized monitoring equipment

Furthermore, EIAs typically disregard the ecological resilience of impacted systems, including their natural capacity to absorb, process, or recover from disturbances. By ignoring self-cleansing and ecosystem feedback, assessments often overestimate short-term impacts and underestimate long-term degradation.

Existing EIAs are static and ill-suited for the modern challenges of climate volatility and urban growth. Lacking dynamic data, spatiotemporal modeling, and post-approval accountability, they fail to manage cumulative impacts from multiple projects. This approach contrasts with the transparency and public participation goals of the Aarhus Convention, as periodic, disconnected reports hinder true access to justice and effective environmental governance.

Based on a review of over 100 project case studies, construction-phase measures are highly prescriptive and focus on mitigating immediate impacts. Common mandates include dust suppression (e.g., watering surfaces and covering materials), soil and water protection (e.g., maintained machinery and spill kits), and ecological safeguards like restricting vegetation clearing to outside of bird nesting season. However, a significant omission is the lack of requirements to systematically monitor the actual consumption of toxic materials onsite; while safe storage is addressed, daily usage is not tracked. This creates a blind spot for waste management due to the untracked “loss” of materials. Over

the long term, this lack of data prevents regulators from assessing the true, cumulative chemical load on a local environment from multiple construction projects.

After project completion, the focus shifts to long-term operational integrity and monitoring. This includes routine infrastructure inspections, mandatory emissions monitoring, and lifecycle management for components like solar panels. Unique requirements involve multi-year ecological studies, such as monitoring for invasive species or assessing bird and bat mortality at wind farms. Stricter measures apply to high-risk industries, including continuous air and soil testing for heavy metals and detailed chemical consumption logs at pharmaceutical plants.

Projects deemed to have minor or manageable impacts are often exempt from a full EIA based on their limited scale or location. While these projects must still legally comply with environmental rules, a critical gap often exists in the inconsistent enforcement and onsite monitoring of these measures. This practice raises a crucial question as to whether the cumulative environmental impact of multiple exempt projects, especially when considering their increasingly trackable supply chains, is significantly underestimated.

As noted earlier, natural self-cleansing capacities remain insufficiently integrated into EIA practice. Mitigation strategies overwhelmingly rely on technical and procedural interventions, with little mention of leveraging the environment's inherent capacity for pollution control, such as through bioremediation or natural water filtration, indicating a clear preference for engineered solutions.

3.3. Potential of Natural Self-Cleansing Mechanisms

The preceding analysis indicates a key flaw in current environmental governance. Ecosystems are often treated as passive sites that simply receive pollution, ignoring their natural ability to recover. This view leads to underestimating long-term damage and misses chances for smarter, sustainable development. Therefore, natural self-cleansing processes, which define an ecosystem's ability to absorb impacts, must become a central part of environmental assessments.

There are two main reasons to better measure these processes. First, the environment's capacity to clean itself is a limited resource that can be exhausted by excessive pollution, so it must be protected. Second, understanding this capacity allows us to create more accurate models that predict how an ecosystem will actually respond to new projects. Acknowledging this dual role of protection and prediction is the foundation for better, science-based assessment models. The first step is to categorize the key self-cleansing mechanisms. As detailed in Table 5, these mechanisms include the following:

- *Physical processes:* dispersion, deposition (air, water), sedimentation (water), leaching (soil), aggregation, and soil structuring (e.g., dilution and volatilization).
- *Chemical processes:* oxidation (e.g., ozone degrading pollutants), reduction, photolysis, hydrolysis, and complexation.
- *Biological processes:* photosynthesis, phytoremediation, nitrogen fixation, microbial decomposition, and filtration (e.g., vegetative uptake and microbial action).
- Several mechanisms may be combined, e.g., in the natural attenuation [54] of soil.

3.4. Interplay: Construction Impacts and Environmental Self-Healing

The capacity for natural self-cleansing depends on substance saturation and many other local factors. The actual area of influence and pollutant distribution due to construction depend on paths (logistics); work types; the type of equipment used; and natural conditions, such as topography, microclimate, and weather. Therefore, static maps of self-cleansing that could be used in planning are, in general, not feasible.

Co-existing cumulative effects, as well as the presence of flora and fauna, determine self-healing dynamics and limitations, which are influenced by seasonal and even daily factors, such as atmospheric oxidants [55,56]. The natural dynamics are very intense, though self-cleaning capacity maps can be developed [57]. The levels vary in the case of oxidants, with up to 20% additional oxidants. Furthermore, the oxidants are very difficult to measure directly, as the molecule has a lifetime of less than one second [58], which is measured indirectly through gas traces [55,58]. The potential for decarbonization through photosynthesis has been extensively studied [59], and it is monitored and visualized through forestry flux maps [60,61]. Self-cleansing is also mimicked in building materials with very efficient inherent properties [62,63]. For example, self-cleaning concrete [64] and photovoltaic panels [65] utilize droplet flow [66].

Table 5. Natural self-cleansing mechanisms and applications, including made surfaces.

Citation	Key Mechanism/Focus and Pollutant/Concept	Process Types Studied			Natural Resource Pollution			Made Surfaces
		Physical	Chemical	Biological	Air	Water	Soil	Surfaces
[67]	anaerobic biodegradability, hydrolysis		x	x		x	x	
[66]	film and droplet flow surfaces	x			x			x
[68]	water pollution thresholds	x	x	x		x		
[69]	attenuation of PFAS for coatings	x	x				x	
[70]	dispersion of dust and gases	x			x			x
[64]	concrete self-cleaning	x	x					x
[71]	adsorption by plant barks	x		x	x			
[72]	photolysis applications		x		x	x	x	
[73]	impact of green walls	x	x	x	x			
[74]	chemometrics		x			x		
[75]	natural filtration and other mechanisms	x	x	x		x	x	
[61]	forest CO ₂ fluxes	x		x	x			
[76]	sedimentation basins with nanomaterials	x	x	x		x		
[77]	species suitable for SO ₂ /dust		x	x	x			
[55]	oxidation of pollutants and GHG		x		x			
[58]	hydroxyl and pollutants/GHG		x		x			
[78]	traffic-caused soil pollution	x	x				x	
[79]	petroleum self-cleansing	x	x	x			x	
[80]	phytoremediation to absorb, adsorb, and metabolize			x	x			
[56]	hydroxyl in troposphere		x		x			
[81]	free-radical self-cleaning		x		x			
[57]	atmospheric oxidation, PM	x	x		x			
[54]	attenuation	x	x	x			x	
[82]	organic compounds		x	x			x	
[83]	sedimentation	x					x	
[84]	microorganisms			x		x		
[85]	surface self-cleaning	x	x		x			x
[63]	coating	x	x					x
[86]	photolysis		x					
[87]	natural filtration	x					x	
[65]	anti-reflection and permeability	x			x			x
[88]	biodegradation of plastics			x		x	x	
[89]	natural filtration	x				x		
[90]	vegetation in urban parks	x		x	x			
[91]	CO ₂ capture absorption, adsorption	x	x		x			x
[92]	mimic nature: lotus effect, slippery, dry cleaning, super-hydrophobic and paleophobic	x			x			x
[93]	vegetation deposition and dispersion	x		x	x			
[94]	nanoflower for antibiotics		x	x			x	
[95]	microorganisms			x		x		
[96]	plant-microbe phytoremediation			x	x			
[97]	adsorption and dilution	x	x		x	x		
[98]	adsorption of chromate	x	x					
[99]	oxidation of ammonia nitrogen		x	x			x	

3.5. Critical Role of Time in Environmental Risk Mitigation

The variable and unpredictable progress of construction projects (e.g., delays and issues), coupled with the cumulative impacts from the co-existing activities from multiple sites and their supply chains, makes environmental control difficult. Furthermore, the very specific conditions onsite during specific construction activities are unpredictable and not adequately considered.

Consequently, the detailed timing needed for informed decisions is often lacking, resulting in sporadic management of emissions and limited utilization of natural self-cleansing capacity. Spellerberg [100] emphasized that it is important to “Enable timely access to and effective application of relevant, credible, integrated environmental information in support of decision making. . .”.

Time is critical for reducing the environmental impacts of construction from multiple perspectives, encompassing stakeholders, activities, and technical systems. Timely information is paramount for the early detection of environmental issues, enabling informed follow-up decision making, effective planning and resource allocation, and facilitating necessary rapid response and appropriate mitigation. This characteristic is particularly critical in the event of sudden catastrophic environmental pollution, such as spills or structural collapses, where prompt information about site conditions and the affected ecosystem is vital. Hastings [101] stressed that “The consideration of timescales and dynamics is needed for the understanding of fundamental issues in ecology.”

Despite growing awareness of the construction sector’s environmental burden, currently employed practices offer limited insight into when, where, and, unless disastrous, why particular pollution actually occurs, and are unable to incorporate the natural “helping hand” that enables the adaptive, self-regulating capacities of natural systems. By ignoring these dynamic ecological processes, project designs miss crucial opportunities for synergy, instead relying on costly and energy-intensive engineered solutions. This characteristic leaves decision makers without the timely information, feedback mechanisms, or spatial intelligence necessary to act and adapt when necessary.

What is missing is a coherent framework that integrates real-time environmental sensing, digital permitting, publicly available and site-specific data, and ecological models into a continuously learning, spatially explicit system.

In the following section, we present the 5D EIA framework as a solution to this critical governance and knowledge gap.

4. I-EDSIS: A Paradigm Shift Toward Dynamic Environmental Control

To address the limitations of currently employed EIA practices in construction, including their static nature, reliance on document-centric processes, and inadequate handling of dynamic, cumulative, and ecosystem-level impacts, a paradigm shift is needed.

4.1. TO-BE: Synthesis of Digital Environmental Monitoring and Assessment

The Integrated Environmental Decision Support Information System (I-EDSIS) is a proactive framework designed to transform EIA. Building on insights from digital twin, urban metabolism, and circular economy (see Section 2), I-EDSIS integrates BIM, sensors, and ecological models into a governance-oriented system. Critically, it also integrates this with available cross-sectoral data, such as public weather forecasts and biodiversity databases, as well as proprietary information, including blockchain-based material passports.

As illustrated in the To-Be re-engineered process in Figure 5, this comprehensive data integration allows I-EDSIS to provide continuous, real-time impact analysis and predictive insights. It addresses current gaps by creating a dynamic control system that supports sustainable development and aligns with frameworks like the EU Taxonomy [102].

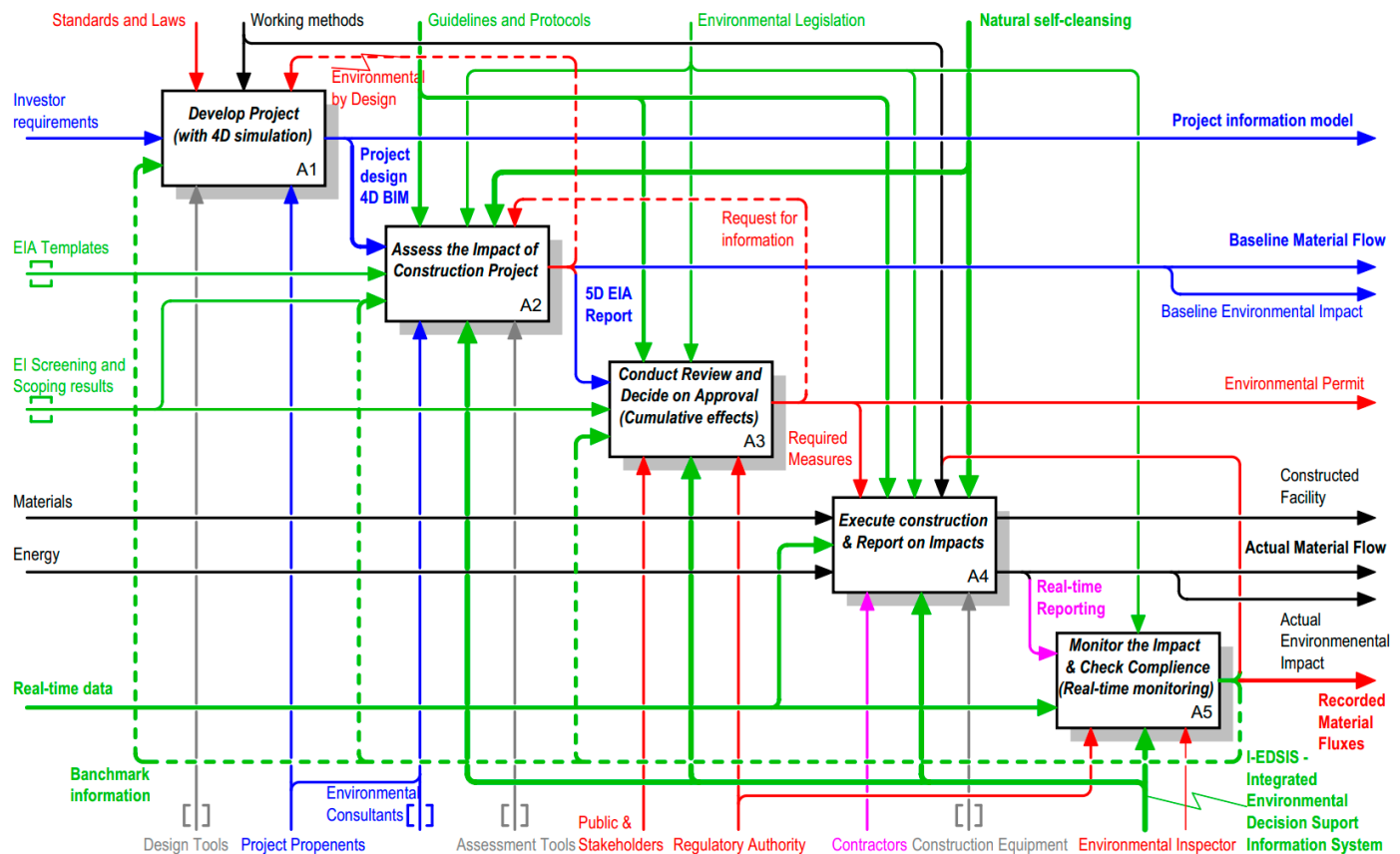


Figure 5. To-Be process for 5D EIA (environmental impact assessment) with baseline and actual information (material flows and environmental assessment) with feedback loops supported by an integrated environmental system featuring cumulative real-time data and benchmark information. Blue denotes project development information flows, red denotes permitting and inspection flows, black denotes on-site material and energy flows, green denotes flows related to greening and sustainability, and dashed lines represent optional flows. The bold green line denotes the novelty proposed in this study and green dashed bold lines indicate newly introduced feedback loops.

A central feature of the To-Be model is its explicit integration of cumulative effects, evaluated during the “Conduct Review and Decide on Approval” (A3). This process shifts the EIA toward assessing a project’s combined 4D/5D impact over time, considering other regional activities and real-life conditions.

Crucially, two types of benchmark information—data from other projects reflecting cumulative effects and in-project benchmark data—serve as vital inputs that influence multiple stages, starting from initial project development (A1). This information, which encompasses 4D construction progress, material/energy flows, and accumulated environmental impacts, guides early design and planning, thereby enabling subsequent adaptation and auditing.

The step “Execute Construction and Report on Impacts” (A4), which enables the analysis of actual material flow and actual environmental impact, can be recorded as “Recorded Material Fluxes” through “Real-Time Monitoring” (A5) as key activities within the I-EDSIS. Unlike the static nature of traditional EIA reports and the periodic review cycles of many EMSs, the I-EDSIS is engineered for continuous real-time data assimilation and dynamic impact assessment. This characteristic contrasts with the delayed, sporadic, or lack of timely data monitoring in the As-Is process.

The following process elements are substantially reengineered in I-EDSIS:

- Inputs: Real-time monitoring is included in environmental control.

- Controls: Guidelines and protocols, new legislation, and natural cleansing.
- Outputs: New technologies enable better simulation and control of material flows, allowing for the capture of both baseline and actual material flows. Outputs from other EIA processes are stored in benchmarks for follow-up projects.
- Mechanism: The overall process is supported by the I-EDSIS.

The solutions listed in the supplement, along with eco-innovations, could be better utilized and their impact monitored. I-EDSIS could connect local weather, permit requirements, EMS data, and biodiversity databases [103,104]. Furthermore, digital passports, digital building logbooks, waste exchange centers, and I-EDSIS could be utilized to access valuable data on material streams, thereby facilitating circularity.

4.2. Case Studies: Dynamic Spatiotemporal Analysis

Large construction sites, due to their scale and duration, are temporary high-impact industrial zones that demand rigorous environmental oversight for key emissions (e.g., PM, SO₂, and NO_x). Traditional static, periodic monitoring often fails to capture real-time changes or cumulative effects in these dynamic settings. The importance of dynamic, data-driven strategies is underscored by studies, such as those on China's cement sector [105], where real-time monitoring reveals substantial abatement potential for pollutants relevant to the construction footprint. This finding underscores the crucial need for such advanced approaches to provide timely insights and facilitate adaptive management.

Here, we demonstrate how I-EDSIS, which uses continuous data acquisition, integrated analysis, and dynamic simulation, significantly improves environmental performance and decision making in construction. I-EDSIS can be implemented incrementally from existing datasets to support real-time monitoring and advanced real-time analytics as capabilities mature. Two scenarios illustrate the practical application and transformative potential of the I-EDSIS over static assessments:

- Scenario 1: Beyond Hindsight—4D BIM-Based Proactive Eco-Construction. This scenario demonstrates project-level predictive modeling and adaptive mitigation using integrated 4D/5D data and considers natural self-cleansing.
- Scenario 2: Empirical Insights Into Spatiotemporal and Cumulative Impact Control. Informed by national pollution case studies, wide urban/regional impacts are evaluated in this scenario by analyzing data from all regional construction projects (including minor projects) to manage their cumulative effects.

These demonstrations highlight how this data-driven approach facilitates more effective, proactive, and adaptive environmental governance for small and large construction sites. The presented applications of I-EDSIS principles are geographically and broadly transferable. Jurisdictions with accessible environmental, permit, and spatial data can adapt the model, given institutional will and digital interoperability.

4.2.1. Scenario 1: Beyond Hindsight—4D BIM-Based Proactive Eco-Construction

Central to prospectively assessing construction-related environmental loads are 4D building information models (BIMs). These models combine 3D representations of structural or nonstructural elements with a scheduled erection time (4D). Each 3D element is further enriched with critical metadata, encompassing the physical properties of the materials used (e.g., volume, weight, heat capacity, and permeability); functional and non-functional descriptors; and environmentally important data, such as the solar reflectance index, embodied energy, and CO₂ footprint. Importantly, each element can be constructed through various methods (e.g., fabricated onsite or prefabricated offsite), with the selected approach acting as a specific “recipe” dictating the precise materials (“ingredients”), equipment (“tools”), and labor (“chefs”)—all of which contribute their own environmental

footprints. When applied across element-by-element schedules for construction, a comprehensive 5D overview of the baseline environmental burden and material flow of the supply chain for the facility lifecycle can be provided.

As construction proceeds, progress monitoring leverages schedule updates and real-time data from onsite cameras and sensors, and the obtained information can be used to construct environmental simulation and dynamic construction progress models. This synergy enables robust evaluation of the actual environmental burden as it unfolds on-site impact. Linked digital product passports (DPPs) allow for retroactive assessment of the impacts of the supply chain.

The resulting rich, multifaceted data streams from BIM, construction recipes, DPPs, live environmental monitoring, and simulations can be powerfully leveraged by AI. Crucially, over time, the system learns from the continuous influx of data and can suggest when it is spatiotemporally most environmentally appropriate to execute specific construction works (see Scenario 2).

In addition, the system's ability can be enhanced such that when a new facility is being designed, the I-EDSIS can predict its environmental footprint with increasing accuracy. This integrated, data-driven approach directly supports proactive environmental management from the earliest design and planning stages, guiding the selection of the "best recipe" for construction and ultimately promoting a genuinely sustainable interaction between the built and natural environments.

4.2.2. Scenario 2: Empirical Insights into Spatiotemporal and Cumulative Impact Control

The empirical basis for this analysis primarily comprised five years (2017–2021) of historical hourly air quality data for five pollutants:

- Particulate matter (PM₁₀ and PM_{2.5});
- Ozone (O₃);
- Sulfur dioxide (SO₂);
- Nitrogen oxide (NO_x);
- Carbon oxide (CO).

Data from all Slovenian monitoring stations was provided by the Slovenian Environmental Agency (ARSO). This extensive dataset of several million location–time–type–value points was contextualized using information on demographic, waste, and statistics on issued permits from the Statistical Office of the Republic of Slovenia (SURS); EIA environmental permits from the Ministry of Environment, Climate and Energy (MOPE); and GIS data, including cadastre and topographic maps, from the Surveying and Mapping Authority (GURS).

Figure 6 illustrates the temporal scales (yearly, monthly, weekly, and hourly) for the five monitored pollutants (PM₁₀, O₃, SO₂, NO_x, and CO), including insights from statistical uncertainty measures such as the standard error of the mean (SEM).

The following observations can be made:

- PM₁₀ (Particulate Matter 10 µm): Yearly averages ranged between 26 and 35 µg/m³, remaining below the 40 µg/m³ annual limit. Monthly peaks occurred in winter (December–February), with values reaching ~37 µg/m³, while the summer months dropped below 20 µg/m³. SEM reached up to ±1.8 µg/m³. Weekday concentrations were generally higher (~30 µg/m³) than weekends (~26 µg/m³). Hourly values showed two peaks, around 08:00 and 21:00, corresponding to traffic and heating activities. Exceedance of the daily limit (50 µg/m³) occurred more than 35 times per year in some regions.
- Ozone (O₃): Yearly means were stable around 60–65 µg/m³. Monthly peaks appeared in July–August (up to 80 µg/m³), while January values dipped to ~35 µg/m³. SEM

reached $\pm 3.2 \mu\text{g}/\text{m}^3$. Weekend levels were higher than weekdays (~ 64 vs. $57 \mu\text{g}/\text{m}^3$), reflecting less NO titration. Hourly patterns showed a strong peak in the afternoon (15:00–16:00). The 8-h mean of $120 \mu\text{g}/\text{m}^3$ was exceeded on more than 25 days in multiple years, breaching the three-year rolling threshold.

- Sulfur Dioxide (SO_2): Yearly means remained low ($\sim 4\text{--}8 \mu\text{g}/\text{m}^3$), well within the $20 \mu\text{g}/\text{m}^3$ ecosystem threshold. Monthly peaks occurred in winter ($\sim 7.8 \mu\text{g}/\text{m}^3$ in January), with SEM around $\pm 0.5 \mu\text{g}/\text{m}^3$. Hourly and daily patterns were relatively flat with no significant exceedances. All legal limits (hourly and daily) were respected.
- Nitrogen Oxides (NO_x): Annual averages decreased from $\sim 50 \mu\text{g}/\text{m}^3$ to $\sim 35 \mu\text{g}/\text{m}^3$ over the 5-year span. The winter months recorded the highest values. Hourly data showed distinct traffic-related peaks at 08:00 and after 16:00. Weekdays averages 10–15% higher than weekends, note the differences between the orange and blue curves over the columns. The annual average remained generally within the $40 \mu\text{g}/\text{m}^3$ NO_2 threshold, although short-term exceedances could not be conclusively verified as critical.
- Carbon Monoxide (CO): Yearly averages ranged from 0.7 to $1.0 \text{ mg}/\text{m}^3$ ($700\text{--}1000 \mu\text{g}/\text{m}^3$), safely within the $10 \text{ mg}/\text{m}^3$ limit. Monthly values peaked in winter ($\sim 1.1 \text{ mg}/\text{m}^3$), and SEM was relatively low (up to $\pm 0.04 \text{ mg}/\text{m}^3$). Hourly patterns revealed peaks at 08:00 and late at night, confirming traffic emissions as the dominant source. Overall, carbon monoxide (CO) levels were not critical, remaining well below the regulatory threshold throughout the observation period.

Correlation and Regression Analysis. The correlation analysis reveals a strong positive correlation between the number of building permits and the concentrations of NO_x ($r = 0.97$), CO ($r = 0.96$), and PM_{10} ($r = 0.96$) in the same year. These relationships are confirmed through linear regression, where building permits explain a significant portion of the variance in pollutant levels— $R^2 = 0.95$ for NO_x , 0.91 for CO, and 0.92 for PM_{10} . Correlation analysis revealed strong associations between PM_{10} and NO_x ($R > 0.7$), especially in urbanized areas. Each additional building permit is associated with a rise of $\sim 0.005 \mu\text{g}/\text{m}^3$ in NO_x and PM_{10} . CO and NO_x also showed a significant positive correlation during traffic-related peak hours. An inverse correlation was observed between NO_x and O_3 during the day, highlighting the effects of photochemical titration.

Multiple linear regression identified NO_x , SO_2 , and meteorological variables as significant predictors of PM_{10} levels. Variance inflation factor (VIF) values were all below 5, indicating low multicollinearity and supporting the robustness of the regression model.

Additionally, a strong correlation was observed between PM_{10} and $\text{PM}_{2.5}$, justifying the exclusion of $\text{PM}_{2.5}$ from separate visual analysis. Pollutant levels vary strongly by time: concentrations often double or triple across hours or between months, with winter levels higher than in summer.

Implications for Construction Activities. The results emphasize that construction activities should be scheduled and managed in a way that minimizes pollutant release during vulnerable periods. Specifically, activities should be limited during winter months, early mornings, and late evenings and coordinated to avoid amplifying weekday traffic-related peaks. Dust-generating construction may have reduced impact between April and September, particularly in May, during the initial two working days (Monday and Tuesday) in morning hours (7–10). Construction logistics planning should incorporate these air quality dynamics to reduce environmental impact and health risks.

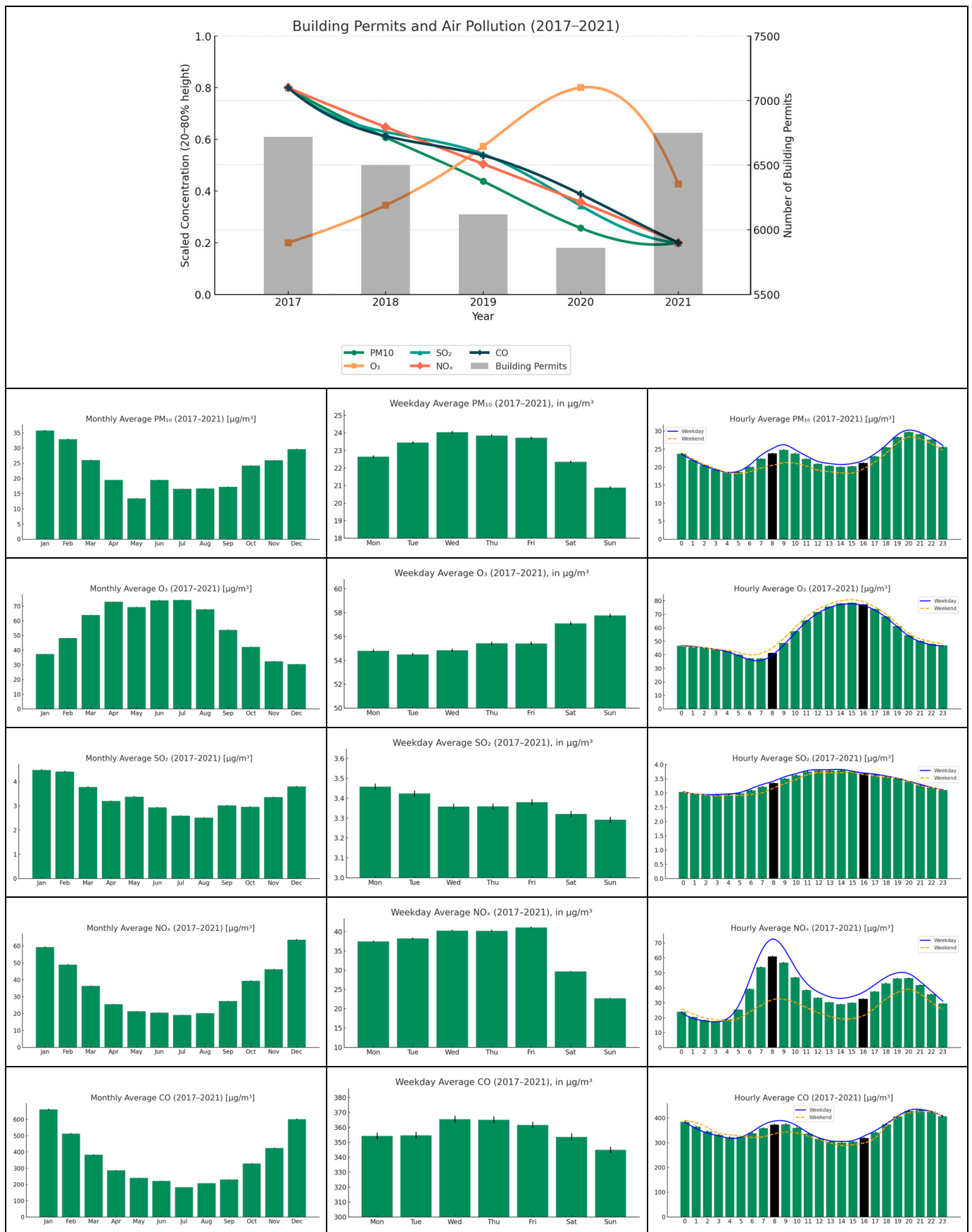


Figure 6. Concentrations of PM₁₀, O₃, SO₂, NO_x, and CO from the years 2017 to 2021 in Slovenia. (Sample data: several million records from 24 measuring nation locations. Source of data: ARSO) Note: vertical black lines on columns indicate standard error margins.

The Slovenian case study compellingly demonstrates how the core principles of the I-EDSIS framework—specifically, dynamic monitoring, time-based simulation, and contextual interpretation—are effectively grounded in empirical data. Furthermore, this study highlights the practical value of integrating spatiotemporal intelligence into environmental assessments, particularly when it is visualized using graphical representations within a GIS context. These GIS tools, which enable area-specific views and the overlay of relevant data to expose and assess cumulative effects within an area of influence, significantly increase the effectiveness of environmental management. Figure 7 illustrates the crucial role that visualization and robust information management play in facilitating informed decision making.

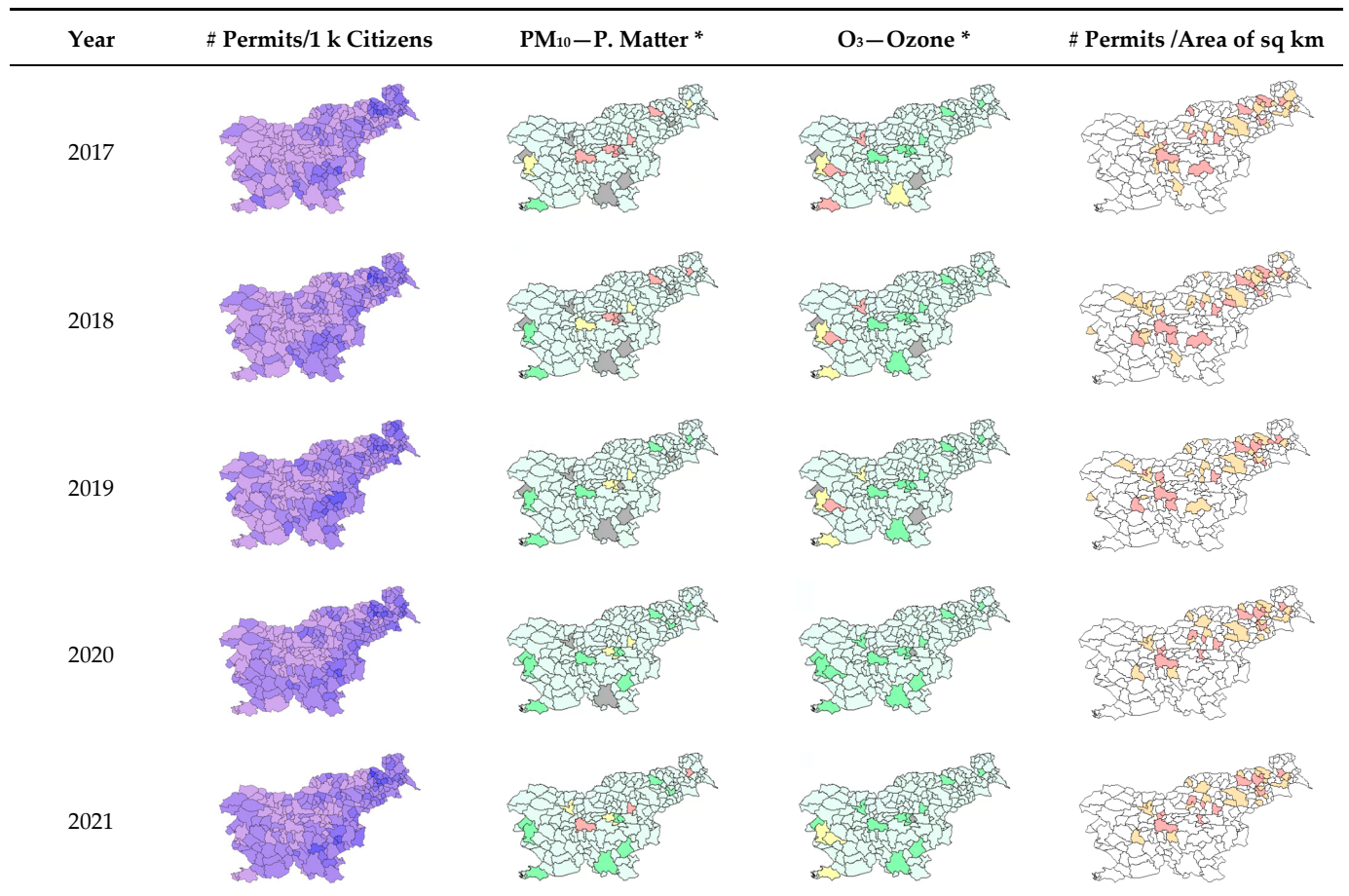


Figure 7. (Left) issued building permits (darker means more building permits per 1000 citizens). (Right) building permits of construction per square kilometer of land (red means double the average, orange over average, green acceptable values, grey areas denote incomplete pollutant data). * Air pollutants—particulate matter (PM₁₀) and ozone (O₃)—are more closely linked to the representation of building permits per km² than to the number of permits per 1000 citizens in an area.

The analysis of empirical data reveals pollutant variability and influencing patterns that underpin the advantages of I-EDSIS for adaptive environmental management. Full implementation would require richer datasets, many of which are publicly available, and specific data such as soil data (contamination/attenuation), hydrological/ecological data (water purification), and microclimate information (dispersion), to comprehensively assess natural self-cleansing. Such integration would allow for leveraging natural attenuation, developing explicit risk maps reflecting varying cleansing capacities, and conducting regional cumulative depletion modeling of this ecosystem service, thereby enhancing assessments.

The I-EDSIS makes use of empirically grounded principles, moving beyond the limitations of traditional static assessments. This system can transform an EIA from a reactive compliance into a dynamic engine for proactive environmental foresight and adaptive governance. The added value, novelty, and contrast to conventional impact control methods are demonstrated through several practical applications, for example:

- For targeted real-time intervention, the I-EDSIS addresses the common struggle of identifying pollution sources promptly. Conventional responses to particulate matter (PM) spikes, for instance, often involve general health alerts that are ineffective for source mitigation. The I-EDSIS, however, offers immediate precision. Upon detecting elevated PM levels, this system cross-references real-time environmental sensor data with 4D digital construction models and meteorological inputs to pinpoint the specific source (e.g., “Construction Project X” excavation under unfavorable winds). Instead of issuing broad warnings, authorities can target specific requests to contractors for immediate operational adjustments, such as intensified dust suppression. This process creates a rapid, data-driven feedback loop, reducing source emissions typically within hours—in stark contrast to delayed or omitted generalized traditional responses—and provides a verified audit trail for compliance and accountability (supporting the polluter pays principle (PPP)).
- In proactive impact minimization by scheduling, the I-EDSIS introduces critical temporal intelligence, challenging traditional permitting systems that treat time statically. By analyzing historical air quality data (as exemplified by the Slovenian dataset) and real-time meteorological forecasts, the I-EDSIS identifies optimal, low-impact time windows characterized by favorable atmospheric dispersion and low cumulative pollution loads. When a high-impact activity such as demolition (“Construction Project Y”) is planned, the I-EDSIS runs predictive simulations to recommend these optimal windows (e.g., mid-week mornings). This could enable project managers to adaptively schedule activities, minimizing exposure and the risk of regulatory breaches.
- Furthermore, for coordinated governance and urban circularity, the I-EDSIS enables urban-scale orchestration, moving beyond current EIA practices that often involve evaluating projects in isolation. By integrating permitting schedules, data on environmental carrying capacities, and vulnerability mapping, the system can identify potential environmental overloads resulting from multiple simultaneous high-emission activities within a district. This characteristic allows urban planners to proactively renegotiate timelines and stagger peak activities, balancing development with environmental resilience. Simultaneously, the I-EDSIS interfaces with demolition site BIMs to identify reusable materials (e.g., concrete and steel) before demolition. The system then alerts material recovery firms and municipalities, facilitating the preemptive diversion of valuable resources from landfills. In this manner, the I-EDSIS not only mitigates emissions but also actively catalyzes circularity, directly linking environmental intelligence with material stewardship. This approach supports the shortest routes for material and waste management.

4.3. Summary of Distinct Features and Critique of the Solution

These findings align with our gap analysis (Table 4), which identifies inconsistent information, the inherently static nature of current EIA practices, and insufficient live monitoring of dynamic on-site conditions as critical weaknesses. The observed variability and evidence of cumulative impacts emphasize the imperative to integrate real-time data overlays for accurately capturing dynamic environmental shifts and evaluating the true effectiveness of on-site mitigation measures. The I-EDSIS could then use weather forecasts, local conditions and dynamic construction plans to dynamically adjust the predicted short-

term impact of activities or suggest optimal work windows. For example, high wind speed can enhance dispersion, while wind direction determines pollutant transport pathways. The I-EDSIS could incorporate wind forecasts to model plume dispersion and assess risks to sensitive nearby ecosystems or communities, dynamically adjusting mitigation needs.

To highlight the originality of the proposed framework, it is useful to compare the I-EDSIS with related approaches, such as digital twins and strategic environmental assessment (SEA). Table 6 summarizes their respective focus, typical data sources, and limitations.

Table 6. Comparison of I-EDSIS with related frameworks.

Framework	Focus and Scale	Typical Data Sources	Limitations
Digital Twin	Real-time modeling of assets, buildings, or infrastructure at project level.	IoT sensors and other sensor and operational data, BIM, GIS, simulation models.	Domain specific; Techno-centric, asset-level; limited governance integration; not for legal enforcement.
SEA (Strategic Environmental Assessment)	Policy, plan, and program level, regional/national scale, evaluates broader impacts.	Reports, planning data, stakeholder inputs, scenario models, expert judgement.	Often generic; lacks real-time data; weak follow-up and cumulative impact analysis.
EMS (Environmental Management Systems)	Organizational and project-level continuous improvement, to comply with standards, e.g., ISO 14001.	Environmental performance indicators, audits, compliance records.	Compliance-driven; limited to organizational scope; not cumulative or systemic; not linked to cross-sectorial data.
LCA (Life Cycle Assessment)	Product, process, or building level; retrospective or scenario-based.	Inventory databases, emission factors, life-cycle datasets.	Static, backward-looking; limited governance role; does not capture real-time or cumulative effects.
Urban Metabolism	City or regional scale; analysis of material and energy flows.	Statistical data, resource flow accounts, sometimes LCA coupling.	Data-intensive; focus on flows not impacts; weak governance integration.
I-EDSIS (proposed)	Project-to-regional scale; governance-oriented integration of monitoring, modeling, and decision support.	Real-time spatiotemporal monitoring, BIM, ecological models, national datasets, stakeholder inputs.	Still conceptual; requires implementation and validation; needs institutional adoption.

I-EDSIS is conceived as both a project-level and strategic integrator. It is designed to be used not only in project design and construction, but also in larger-scale development contexts. Its distinct contribution lies in integrating multiple cross-sectoral data sources—including biodiversity databases, meteorological stations, and environmental monitoring networks—alongside conventional construction and operational data. Furthermore, I-EDSIS is designed to serve as an overarching system that connects and orchestrates multiple domain-specific digital twins (e.g., those of construction sites, existing power plants, infrastructure assets, or ecosystems), embedding them within a governance-oriented framework. This enables temporary digital twins to be seamlessly integrated into long-term operational twins, ensuring continuity across project life cycles.

In addition, I-EDSIS incorporates features linked to materials, such as digital material passports, advanced on-site monitoring, and simulations through 5D BIM. Over time, these capabilities would reveal even greater advantages by enabling transparent tracking of material flows; improving circularity; and supporting evidence-based decision making across construction, operation, and deconstruction phases.

Compared with SEA and EMS, which remain document-centric and procedural, I-EDSIS combines real-time monitoring, adaptive scheduling, cross-sectoral datasets, and accountability mechanisms into a unified framework that addresses both technical and institutional gaps. This combination of technical integration, material intelligence, and governance orientation highlights the originality of I-EDSIS.

EIA-related analysis and simulations typically require integration of data from heterogeneous sources such as proprietary sensor data, data from environmental agencies, statistical offices, and surveying authorities. Data in various formats, resolutions, and qualities must be integrated. Furthermore, access to the necessary data may be restricted

by technical barriers or policies. This highlights the importance of ensuring data quality and accessibility for successful I-EDSIS implementation.

Appendix A, Table A1 highlights a wide range of innovative technologies in design, construction, and operation that reduce environmental impact across key dimensions—materials, energy, emissions, water, and waste. These approaches not only contribute to sustainability goals but also directly support the I-EDISS framework by enabling real-time monitoring, predictive control, and digital documentation (e.g., BIM, IoT, digital twins). By integrating such technologies, construction activities can be aligned with environmental regulations and achieve measurable reductions in ecological footprint.

However, Real-time monitoring—a core component of I-EDSIS—requires the use of appropriate on-site monitoring equipment, with selection depending on the specific environmental parameters being monitored (e.g., air, water, soil, and noise). Critical equipment factors include sensor accuracy, precision, sensitivity, reliability, and durability. The spatial distribution and temporal frequency of monitoring devices are also important for capturing the dynamic nature of environmental impacts.

Despite advances in sensor and IoT technologies, public-facing real-time environmental dashboards for large construction sites remain uncommon. Several factors contribute to this: ensuring sensor accuracy in dynamic environments is challenging, and integrating diverse data sources often lacks standardization. While dynamic sensing tools exist, connecting them to platforms like I-EDSIS requires reliable data transmission, bandwidth, and visualization tools tailored for diverse stakeholders.

Various systems must also meet stringent privacy and cybersecurity standards, particularly under regulations such as the GDPR in the EU and the CCPA in the U.S., as well as other sector-specific data protection requirements. Additionally, real-time disclosure may expose non-compliance or inefficiencies, raising commercial concerns and limiting willingness to share data openly.

Non-technical barriers further hinder adoption. I-EDSIS cannot resolve deeper issues, such as weak institutional enforcement, fragmented regulations, or inadequate capacity in regulatory bodies. Most environmental laws require periodic reporting, not live data sharing, and the costs of implementing public dashboards remain high. Sociopolitical factors, including public trust and uneven stakeholder influence, also shape environmental governance. While frameworks like I-EDSIS can enhance transparency and participation, their effectiveness depends on broader institutional readiness and commitment to adaptive, accountable oversight. Once I-EDSIS is adopted, the listed technological solutions will be ready for implementation across a wide range of construction projects, enabling higher control over environmental impacts

5. Conclusions

Our empirical analysis of national pollution datasets demonstrated that pollutant levels can fluctuate by up to fivefold across months and days. Such variability highlights the limitations of static reports in accurately capturing dynamic environmental conditions and providing guidance on when impacts are most likely to be severe. These findings confirm the need for a five-dimensional (5D) EIA framework that incorporates dynamic, real-time data with adaptive scheduling, with evidence from a case study reinforcing this conclusion.

Despite current prescriptive mitigation measures, such as dust suppression, spill prevention, and seasonal restrictions on vegetation clearance, systematic monitoring of material and pollutant flows was largely absent. Where long-term obligations were specified, they were inconsistently enforced and seldom supported by real-time data, leaving little room for adaptive management or timely corrective action.

Our analysis revealed governance challenges that significantly undermine the effectiveness of EIA. Fragmented institutional responsibilities, inconsistent enforcement practices, and stakeholder resistance to transparency all limit the capacity of current frameworks to prevent or mitigate impacts. Without addressing these institutional barriers, the technical potential of 5D EIA and the I-EDSIS framework will remain underutilized. Linking live monitoring to transparent dashboards, standardized enforcement mechanisms, and accessible reporting is therefore essential to translating empirical data into accountable governance and building trust among stakeholders.

Taken together, the empirical evidence from both national datasets and project-level case studies underscores the urgency of reforming EIA practice. Technical advances alone are insufficient if not matched by stronger governance and enforcement mechanisms. To respond to these challenges, the following priorities (P1–P5) are proposed. They provide a structured roadmap for making EIA more adaptive, evidence-based, and sustainability-oriented, while ensuring that empirical findings directly inform future practice.

5.1. Limitations of the Study

While the case study analysis provided valuable insights into gaps in current EIA practice, there are several limitations. First, the findings are context-specific and may not be directly generalizable to other geographical, institutional, or regulatory settings. Second, the scope and quality of available data constrained the depth of some assessments, particularly regarding long-term monitoring and cumulative impacts. Third, the analysis focused on selected dimensions of EIA practice—such as pollutant variability, monitoring gaps, and governance challenges—without providing an exhaustive account of all environmental or socio-economic factors. Finally, as with most qualitative approaches, some degree of interpretive bias may be present despite efforts to triangulate evidence through interviews and secondary data. Recognizing these limitations helps situate the findings and points toward future research, which should expand the empirical base, incorporate additional case contexts, and test the I-EDSIS framework in practice.

I-EDSIS offers a framework to upgrade the EIA by integrating live monitoring, digital technologies, and the consideration of natural self-cleansing capacities. While this approach shows great promise, it is essential to acknowledge potential challenges and limitations. The effectiveness of the decision supported by I-EDSIS hinges on the availability of reliable, relevant, timely, and comprehensive data. I-EDSIS would rely on effective data collection and processing methods, including techniques like automated sensor systems that process the data on the spot [106], manual sampling, remote sensing, and existing databases, each with its own limitations and advantages. Data would also require manual cleaning, validation, transformation, aggregation, and on-line analytical processing, which require robust data management systems with sufficient resources for storage, retrieval, querying, visualization, and reporting.

5.2. Priorities for the Implementation of a Sustainable Approach

The following priorities, derived from the analysis, align with the need to enhance EIA effectiveness, integrate new technologies, and address critical environmental challenges highlighted in this study and in the wider literature:

P1. Prioritizing Key Environmental Dimensions with an Enhanced Assessment:

- **Prioritizing Minimizing Toxicity over Global Warming Potential:** Establishing 5D protocols for monitoring material fluxes, including metrics such as comparative toxicity units (CTUh/CTUe), to quantify and target toxicity reduction.

- **Prioritizing Biodiversity Protection:** Maintaining a fundamental commitment to preserving biodiversity and minimizing the environmental footprint of facilities (e.g., native landscaping and preventing habitat destruction and disconnectivity).

P2. Improving Data, Monitoring, and Adaptive Management through I-EDSIS:

- **Implementing Advanced Environmental Onsite Monitoring:** Providing a digital space operated by regulators with open APIs to leverage innovative and increasingly affordable technologies, e.g., IoT devices and AI-driven systems for live monitoring.
- **Implementing Systematic Auditing and Feedback Loops:** Enabling rigorous verification of mitigation with the proposed 5D system, allowing for a critical evaluation of initial assumptions regarding impact timeliness and reversibility. Such data-driven feedback provides the basis for assessing the actual capacity of natural self-cleansing.

P3. Integrating Sustainability and Circularity into Construction Design Practice:

- **Sustainable Materials and Waste Reduction through Circularity:** Focusing on the use of sustainable materials (recycled content and renewable resources) to reduce raw material impacts and implementing effective waste management programs.
- **Adopting Sustainable Construction Methods:** Employing innovative techniques such as prefabrication and modular, off-site construction to reduce onsite waste, improve resource efficiency, and enhance overall project sustainability performance.
- **Optimizing Energy Management:** Focusing on substantially reducing energy consumption during construction and operation through efficiency measures and strategic investment in renewable sources to decrease the use of fossil fuels.

P4. Strengthening Governance, Transparency, and Stakeholder Engagement:

- **Enhancing Sustainability Awareness, Reporting and Engagement:** Actively engaging stakeholders through new communication channels and social media, to improve and facilitate the co-development, analysis and sustainable solutions, aligning with the Aarhus Convention on public participation in environmental matters.
- **Implementing Standardized Sustainability Reporting:** Using the I-EDSIS while considering ISO 14064 [107], interfacing or complementing ISO 14001 [108]-compliant environmental management systems (EMSs), digital material passports, building logbooks, etc.
- **Environmental Workforce Upskilling:** The successful implementation requires parallel efforts in policy development, particularly training/capacity building (upskilling) for users (contractors and regulators) and ensuring effective engagement.

P5. Adaptive Management and Strategic Evaluation of Assessments

- **Introducing Adaptive EIA Management:** Enabling adaptive environmental construction management strategies via continuous analysis, allowing for timely adjustments to practices based on actual impacts and improving environmental outcomes.
- **Supporting Complementary Assessment Strategies:** Providing better connectivity with strategic environmental assessments (SEAs) and alignment with EIAs for more effective environmental governance and related assessments (e.g., social impact (SIA), health impact (HIA), and equality impact (EqIA)) and facilitating resilience thinking and environmental impact design (EID).

Implementing I-EDSIS is economically demanding, requiring agreements on upfront selection and investments in equipment, software, and infrastructure, plus ongoing hardware, software, and personnel costs. However, the construction market, which exceeds USD 15 trillion annually, should be able to support a gradual implementation; furthermore, incentives such as the Data Act in the EU could contribute to quicker gains.

As one of the most resource-intensive and environmentally impactful sectors globally, the construction industry faces growing pressure to improve transparency and accountability, though such efforts are often met with hesitation due to commercial sensitivities and operational complexity. While digital technologies for monitoring emissions, dust, noise, and water quality are becoming increasingly widespread, the public availability of real-time environmental data—including on large-scale public construction project sites—remains very limited. Most real-time systems serve internal compliance or performance purposes, with only a handful of pioneering projects (e.g., Scan-Med Corridor, Denmark; High Speed 2, UK; Neom, Saudi Arabia; and Barangaroo, Australia) offering public-facing dashboards or open-access datasets. With the advent of I-EDSIS framework, environmental dashboards could become common, i.e., not only on projects with significant environmental impacts, but also on those where contractors aim to demonstrate their environmental awareness and commitment to sustainability, along with applied technologies listed in Appendix A, Table A1.

Beyond economic and technical considerations, the implementation of I-EDSIS will depend on overcoming governance challenges. Institutional fragmentation, weak enforcement of EIA obligations, and stakeholder resistance to full transparency remain significant barriers to systemic adoption. By embedding accountability mechanisms and participatory processes into its design, I-EDSIS can help reduce these barriers, but regulatory commitment and institutional alignment will be essential. Future work should therefore examine how legal frameworks and stakeholder incentives can be adapted to support the transition from compliance-driven reporting toward proactive, governance-oriented environmental management.

Funding: This study was partly supported by the University of Ljubljana for Sustainable Society ULTRA Pilot 4. Sustainable Environment. The project is co-financed by the Republic of Slovenia, the Ministry of Higher Education, Science and Innovation, and the European Union—NextGenerationEU. The investment is part of the plan's measures, which are financed by the Recovery and Resilience Facility (<http://noo.gov.si> (accessed on 15 September 2025)).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets analyzed during the study are available from the corresponding author upon request and will be made available through dataset distribution services.

Acknowledgments: The authors gratefully acknowledge the Slovenian Environmental Agency (ARSO) for providing the historical hourly air quality data that were essential for the spatiotemporal and cumulative impact analysis conducted in this research. We also extend our sincere thanks to all the experts who participated in the unstructured interviews; their professional perspectives and real-world insights were invaluable in shaping this study. AI was used for extraction and checking.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

API	Application Programming Interface.
AS-IS	Current State of Practices.
BIMs	Building Information Modelling.
CDW	Construction and Demolition Waste.
CFD	Computational Fluid Dynamics.
CO	Carbon Monoxide.
CTUs	Comparative Toxicity Units.

DPPs	Digital Product Passports.
EEA	European Environment Agency.
EIA	Environmental Impact Assessment.
EID	Environmental Impact Design.
EMS	Environmental Management System.
EU	European Union.
GDP	Gross Domestic Product.
GHG	Greenhouse Gas.
GIS	Geographic Information System.
GPS	Global Positioning System.
HIA	Health Impact Assessment.
ICOM	Input, Control, Output, Mechanism.
I-EDSIS	Integrated Environmental Decision Support Information System.
IDEFØ	Integration DEFinition.
IMS	Integrated Management Systems.
IoT	Internet of Things.
IPO	Input, Process, Output.
LCA	Life Cycle Assessment.
NO _x	Nitrogen Oxide.
PM	Particulate Matter.
PPP	Polluter Pays Principle.
QA/QC	Quality Assurance/Quality Control.
SEA	Strategic Environmental Assessment.
SEM	Standard Error of the Mean.
SIA	Social Impact Assessment.
SO ₂	Sulfur Dioxide.
TO-BE	Future State of Practices.
US EPA	US Environmental Protection Agency.

Appendix A

Table A1. Eco-innovation Technologies for Environmental Construction Management.

Innovative Design, Construction, and Operation Technologies	Reduction in Impact on and/or Use/Amount of				
	Materials	Energy	Waste	Emissions	Water
Common Principles for Environmental Protection					
awareness, education on environmental issues, and training	x	x	x	x	x
regulations and laws compliance, environmental stewardship [109]	x	x	x	x	x
circular regions [110], reduce, reuse, recycle, recover in construction [7]	x	x	x	x	x
green labeling, LEED, BREAM, DGNB certification systems [111]	x	x	x	x	x
lightweight sustainable/smart materials [112], dematerialization [113]	x	x	x	x	x
LCA [114], digital product passports, digital building logbook [115]	x	x	x	x	x
reporting, verification, benchmarking, real-time monitoring [105,116]	x	x	x	x	x
CDW management, waste audits, reduction plans [117]	x		x	x	x
wastewater management systems, treatment [118], remediation [119]			x	x	x
green construction [120], construction, and sustainable goals [121]	x	x	x	x	x
Environmental Design and Planning of Facilities					
net-zero, regen., green design [122], nature-based solutions [123]	x	x	x	x	x
EE design of building envelope and layout, low embodied energy		x		x	
design of energy efficient technologies for HVAC, efficient lighting		x		x	
BIM—4D/5D, reduced waste [124], design for disassembly [125,126]	x	x	x	x	
environmental project management, adaptive scheduling, QA/QC	x	x	x	x	x
alternative site selection, environmentally led design alternatives					
advanced BIM and parametric design, simulation tools (CFD)	x	x	x	x	x

Table A1. Cont.

Innovative Design, Construction, and Operation Technologies	Reduction in Impact on and/or Use/Amount of				
	Materials	Energy	Waste	Emissions	Water
Environmental Construction Management Technologies					
hybrid equipment, E-recovery, electric construction machinery [127]		x		x	
alternative fuels machinery, exhaust gas treatment systems				x	
timely use, smart equipment, temp. power mngmt, IDLE shutdown		x			
low emission power generation, site energy recovery systems	x			x	
telematics, autonomous machinery, industrial robotics [128]	x	x		x	
AI [129], modular construction, prefabrication, off-site construction	x	x	x	x	
supply chain optimization: manufacturing and logistics routing		x	x	x	
GPS equipment tracking, mat. tracking, micro-positioning [130,131]		x		x	
smart dust suppress (ion/ants), dust enclosures, exhaust hoods				x	
spraying/wetting, cleaning (CIP) of equipment, vegetation				x	
weather adjusted methods, smart schedule, low speed, windbreaks				x	x
smart water management, irrigation, harvesting, waterless construction					x
spill response equipment, water protection, site drainage					x
metrology, material weighing, laser scanning, lidar, UAV, mic arrays,	x		x	x	
low carbon mat., CO ₂ negative/green/digital concrete, hempcrete	x	x		x	
5D BIM, digital twin, blockchain, on-site stations, IoT air/water/soil				x	
zero waste construction and advanced construction waste management [132]			x	x	x
Environmental Operation and Facility Management					
smart buildings, IoT, drones, AI, predictive maintenance [133]		x		x	
energy efficiency, renewables, smart grids, efficient MEP		x		x	x
water efficiency, conservation, reduction, greywater, harvesting					x
indoor air quality management, low-emission materials				x	
green cleaning practices, sustainable procurement system			x	x	x

Appendix B

Appendix B.1. Keywords Used for Preliminary Literature Review

SCOPUS:

URL: <https://www.scopus.com/search/form.uri?display=advanced> (accessed on 15 September 2025).

Instructions: Copy and paste query expression in Enter Query String

SearchTerm: Screening

((TITLE-ABS-KEY ("environmental impact assessment") OR TITLE-ABS-KEY (EIA)) AND TITLE-ABS-KEY ("Screening") AND (TITLE-ABS-KEY (construction) OR TITLE-ABS-KEY (infrastructure) OR TITLE-ABS-KEY (building) OR TITLE-ABS-KEY (facilit*))) AND (LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "ENGI"))

SearchTerm: Scoping

((TITLE-ABS-KEY ("environmental impact assessment") OR TITLE-ABS-KEY (EIA)) AND TITLE-ABS-KEY ("Scoping") AND (TITLE-ABS-KEY (construction) OR TITLE-ABS-KEY (infrastructure) OR TITLE-ABS-KEY (building) OR TITLE-ABS-KEY (facilit*))) AND (LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "ENGI"))

SearchTerm: EIA Report OR Statement

((TITLE-ABS-KEY ("environmental impact assessment") OR TITLE-ABS-KEY (EIA)) AND (TITLE-ABS-KEY ("EIA Report") OR TITLE-ABS-KEY ("Statement"))) AND (TITLE-ABS-KEY (construction) OR TITLE-ABS-KEY (infrastructure) OR TITLE-ABS-KEY (building) OR TITLE-ABS-KEY (facilit*))) AND (LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "ENGI"))

SearchTerm: Participation

((TITLE-ABS-KEY ("environmental impact assessment") OR TITLE-ABS-KEY (EIA)) AND TITLE-ABS-KEY ("Participation") AND (TITLE-ABS-KEY (construction) OR TITLE-

ABS-KEY (infrastructure) OR TITLE-ABS-KEY (building) OR TITLE-ABS-KEY (facilit*)) AND (LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "ENGI"))

SearchTerm: Consent* OR Permit*

((TITLE-ABS-KEY ("environmental impact assessment") OR TITLE-ABS-KEY (EIA)) AND (TITLE-ABS-KEY (Consent*) OR TITLE-ABS-KEY (Permit*)) AND (TITLE-ABS-KEY (construction) OR TITLE-ABS-KEY (infrastructure) OR TITLE-ABS-KEY (building) OR TITLE-ABS-KEY (facilit*))) AND (LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "ENGI"))

SearchTerm: Monitoring OR Audit*

((TITLE-ABS-KEY ("environmental impact assessment") OR TITLE-ABS-KEY (EIA)) AND (TITLE-ABS-KEY ("Monitoring") OR TITLE-ABS-KEY (Audit*)) AND (TITLE-ABS-KEY (construction) OR TITLE-ABS-KEY (infrastructure) OR TITLE-ABS-KEY (building) OR TITLE-ABS-KEY (facilit*))) AND (LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "ENGI"))

Google Scholar

URL: <https://www.oecd.org/en/search/publications.html?q=Expression> (accessed on 15 September 2025).

Expression: (intitle: "Environmental Impact Assessment" OR intitle: "EIA") (+construction OR +infrastructure OR +buildings OR +project) + (intitle: "SearchTerm")

SearchTerm:

Screening

URL: [https://scholar.google.com/scholar?hl=en&as_sdt=0,5&q=\(intitle:%22Environmental+Impact+Assessment%22+OR+intitle:%22EIA%22\)++\(+construction+OR++infrastructure+OR++buildings+OR++project\)+++intitle:screening](https://scholar.google.com/scholar?hl=en&as_sdt=0,5&q=(intitle:%22Environmental+Impact+Assessment%22+OR+intitle:%22EIA%22)++(+construction+OR++infrastructure+OR++buildings+OR++project)+++intitle:screening) (accessed on 15 September 2025).

Scoping

URL: [https://scholar.google.com/scholar?hl=en&as_sdt=0,5&q=\(intitle:%22Environmental+Impact+Assessment%22+OR+intitle:%22EIA%22\)++\(+construction+OR++infrastructure+OR++buildings+OR++project\)+++intitle:scoping](https://scholar.google.com/scholar?hl=en&as_sdt=0,5&q=(intitle:%22Environmental+Impact+Assessment%22+OR+intitle:%22EIA%22)++(+construction+OR++infrastructure+OR++buildings+OR++project)+++intitle:scoping) (accessed on 15 September 2025).

EIA report OR statement

URL: [https://scholar.google.com/scholar?hl=en&as_sdt=0,5&q=\(intitle:%22Environmental+Impact+Assessment%22+OR+intitle:%22EIA%22\)++\(+construction+OR++infrastructure+OR++buildings+OR++project\)++\(+intitle:%22EIA+Report%22+OR++intitle:Statement\)](https://scholar.google.com/scholar?hl=en&as_sdt=0,5&q=(intitle:%22Environmental+Impact+Assessment%22+OR+intitle:%22EIA%22)++(+construction+OR++infrastructure+OR++buildings+OR++project)++(+intitle:%22EIA+Report%22+OR++intitle:Statement)) (accessed on 15 September 2025).

Participation

URL: [https://scholar.google.com/scholar?hl=en&as_sdt=0,5&q=\(intitle:%22Environmental+Impact+Assessment%22+OR+intitle:%22EIA%22\)++\(+construction+OR++infrastructure+OR++buildings+OR++project\)++\(+intitle:participation\)](https://scholar.google.com/scholar?hl=en&as_sdt=0,5&q=(intitle:%22Environmental+Impact+Assessment%22+OR+intitle:%22EIA%22)++(+construction+OR++infrastructure+OR++buildings+OR++project)++(+intitle:participation)) (accessed on 15 September 2025).

Consent OR Permit

URL: [https://scholar.google.com/scholar?hl=en&as_sdt=0,5&q=\(intitle:%22Environmental+Impact+Assessment%22+OR+intitle:%22EIA%22\)++\(+construction+OR++infrastructure+OR++buildings+OR++project\)++\(+intitle:%22Consent%22+OR++intitle:Permit*\)](https://scholar.google.com/scholar?hl=en&as_sdt=0,5&q=(intitle:%22Environmental+Impact+Assessment%22+OR+intitle:%22EIA%22)++(+construction+OR++infrastructure+OR++buildings+OR++project)++(+intitle:%22Consent%22+OR++intitle:Permit*)) (accessed on 15 September 2025).

Monitoring OR Audit*

URL: [https://scholar.google.com/scholar?hl=en&as_sdt=0,5&q=\(intitle:%22Environmental+Impact+Assessment%22+OR+intitle:%22EIA%22\)++\(+construction+OR++infrastructure+OR++buildings+OR++project\)++\(+intitle:monitoring+OR++intitle:audit*\)](https://scholar.google.com/scholar?hl=en&as_sdt=0,5&q=(intitle:%22Environmental+Impact+Assessment%22+OR+intitle:%22EIA%22)++(+construction+OR++infrastructure+OR++buildings+OR++project)++(+intitle:monitoring+OR++intitle:audit*)) (accessed on 15 September 2025).

OECD

URL: <https://www.oecd.org/en/publications/oecd-archives/oecd-official-documents.html> (accessed on 15 September 2025).

<https://www.oecd.org/en/publications/oecd-archives/oecd-official-documents.html?orderBy=mostRelevant&page=1&q=-SearchTerms&facetTags=oecd-departments:env> (accessed on 15 September 2025).

Screening | Scoping | Preparation | Participation | Permit | Monitoring or Audit*

Note: Under OECD Directorates: Select: Environment Directorate

EU EEA

URL: <https://www.eea.europa.eu/advanced-search> (accessed on 15 September 2025).

Search terms:

- Screening (EIA Screening)
- Scoping (EIA Scoping)
- Reporting (Environmental Impact Assessment Report—This exact phrase)
- Participation (EIA Participation)
- Permitting (EIA Permit)
- Monitoring (EIA Monitoring)

US EPA

URL: <https://search.epa.gov/epasearch/> (accessed on 15 September 2025).

- Screening (EIA Screening—all of these words)
- Scoping (EIA Scoping—all of these words)
- Reporting (Environmental Impact Statement—This exact phrase)
- Participation (EIA Participation—all of these words)
- Permitting (EIA Permit—all of these words)
- Monitoring (EIA Monitoring—all of these words)

Appendix B.2. Source of EIA Reports and Decisions

Review of Local EIA practices: Slovenia

URL: <https://www.gov.si/podrocja/okolje-in-prostor/okolje/okoljske-presoje/pr edhodni-postopek/> (accessed on 15 September 2025).

Review of Global EIA practices: World Bank

URL: <https://documents.worldbank.org/en/publication/documents-reports/doc advancesearch> (accessed on 15 September 2025).

Appendix B.3. List of Profiles of Interviewees and Interview Questions on EIA

List of Profiles of interviewees

Interviewee 01: Expert on monitoring of air pollution data.

Interviewee 02: Person responsible for issuing building permits.

Interviewee 03: Lead designer with extensive experience in environmental impacts.

Interviewee 04: Construction project manager at a major general contractor.

Interviewee 05: CEO of a construction waste handling company.

Interviewee 06: CTO of a demolition waste handling and recycling company.

Interviewee 07: Mid-management employee at a waste management center.

Interviewee 08: Environmental consultant responsible for construction waste.

Interview questions

Question 01. How early and how effectively are environmental experts and stakeholders typically involved in the design phase of major infrastructure projects?

Question 02. What are the biggest challenges in integrating accurate and cumulative environmental data into early project planning?

Question 03. How often are alternative designs considered from an environmental perspective during design, and what limits this process?

Question 04. What tools or methods do you use to simulate or assess material flow and waste generation throughout the project lifecycle, and what are their limitations?

Question 05. How do you see the role of novel technologies (e.g., digital twins, AI, IoT) in improving the environmental performance of construction projects?

Question 06. What barriers prevent the regular updating and sharing of project information and environmental impacts with the public during the project lifecycle?

Question 07. In your experience, how are contractors equipped and incentivized to monitor environmental impacts during execution?

Question 08. How do current regulations and standards support or hinder dynamic, real-time environmental monitoring and adaptive project management?

Question 09. What prevents the full use of monitoring data to improve future projects and establish effective environmental feedback loops?

Question 10. How could we better detect and simulate cumulative effects over time?

References

1. Lauritzen, E.K. *Construction, Demolition and Disaster Waste Management: An Integrated and Sustainable Approach*; CRC Press: Boca Raton, FL, USA, 2019; ISBN 978-1-351-65007-6.
2. OECD. *OECD Environmental Performance Reviews: Luxembourg 2020*; OECD Environmental Performance Reviews; OECD: Paris, France, 2020; ISBN 978-92-64-87300-1.
3. Janssen, N.A.H.; Hoek, G.; Simic-Lawson, M.; Fischer, P.; van Bree, L.; ten Brink, H.; Keuken, M.; Atkinson, R.W.; Anderson, H.R.; Brunekreef, B.; et al. Black Carbon as an Additional Indicator of the Adverse Health Effects of Airborne Particles Compared with PM 10 and PM 2.5. *Environ. Health Perspect.* **2011**, *119*, 1691–1699. [CrossRef]
4. WHO *Global Air Quality Guidelines*; WHO: Geneva, Switzerland, 2021; ISBN 978-92-4-003422-8.
5. GOV.UK. Emissions of Air Pollutants in the UK—Particulate Matter (PM10 and PM2.5). Available online: <https://www.gov.uk/government/statistics/emissions-of-air-pollutants/emissions-of-air-pollutants-in-the-uk-particulate-matter-pm10-and-pm25> (accessed on 17 July 2022).
6. Azarmi, F.; Kumar, P.; Marsh, D.; Fuller, G. Assessment of the Long-Term Impacts of PM 10 and PM 2.5 Particles from Construction Works on Surrounding Areas. *Environ. Sci. Process. Impacts* **2016**, *18*, 208–221. [CrossRef] [PubMed]
7. Tukker, A.; Behrens, P.; Deetman, S.; Hu, M.; Alejandre, E.M.; Van Der Meide, M.; Zhong, X.; Zhang, C. Circular Construction: Six Key Recommendations. *One Earth* **2023**, *6*, 1425–1429. [CrossRef]
8. Wang, C.; Duan, W.; Cheng, S.; Jiang, K. Emission Inventory and Air Quality Impact of Non-Road Construction Equipment in Different Emission Stages. *Sci. Total Environ.* **2024**, *906*, 167416. [CrossRef] [PubMed]
9. The World Business Council for Sustainable Development (WBCSD) (Ed.) *The Greenhouse Gas Protocol: The GHG Protocol for Project Accounting*; World Business Council for Sustainable Development; World Resources Institute: Geneva, Switzerland; Washington, DC, USA, 2005; Volume 1, ISBN 978-1-56973-598-5.
10. OECD *Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences*; OECD: Paris, France, 2019; ISBN 978-92-64-30744-5.
11. US *The National Environmental Policy Act of 1969*; U.S. EPA: Washington, DC, USA, 1969; p. 7.
12. Council of European Communities Directive 85/337/EEC of 27 June 1985 on the Assessment of the Effects of Certain Public and Private Projects on the Environment. 1985. Available online: <https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A31985L0337> (accessed on 10 August 2025).
13. European Commission *Environmental Impact Assessment of Projects: Guidance on Scoping (Directive 2011/92/EU as Amended by 2014/52/EU)*; Publications Office: Luxembourg, 2017.
14. Fothergill, J.; Murphy, J. *The State of Digital Impact Assessment Practice: A Global Snapshot of the Uptake of Digital Technologies and Approaches within Impact Assessment Practice in 2021*; Fothergill Training & Consulting; International Association for Impact Assessment: Washington, DC, USA, 2021.
15. NASA. Airborne Nitrogen Dioxide Plummets Over China. Available online: <https://earthobservatory.nasa.gov/images/146362/airborne-nitrogen-dioxide-plummets-over-china> (accessed on 26 June 2022).

16. Dasgupta, P.; Srikanth, K. Reduced Air Pollution during COVID-19: Learnings for Sustainability from Indian Cities. *Glob. Transit.* **2020**, *2*, 271–282. [\[CrossRef\]](#)
17. Newburger, E.; Jeffery, A. Photos Show Impact of Temporary Air Pollution Drops Across the World from Coronavirus Lockdown. Available online: <https://www.cnbc.com/2020/04/23/coronavirus-photos-show-effect-of-air-pollution-drops-from-global-lockdown.html> (accessed on 26 June 2022).
18. Otmani, A.; Benchrif, A.; Tahri, M.; Bounakhla, M.; Chakir, E.M.; El Bouch, M.; Krombi, M. Impact of COVID-19 Lockdown on PM₁₀, SO₂ and NO₂ Concentrations in Salé City (Morocco). *Sci. Total Environ.* **2020**, *735*, 139541. [\[CrossRef\]](#)
19. Haghazadeh, H.; Cunningham, J.A.; Kumar, V.; Aghayani, E.; Mehraein, M. COVID-19 and Urban Rivers: Effects of Lockdown Period on Surface Water Pollution and Quality- A Case Study of the Zarjoub River, North of Iran. *Environ. Sci. Pollut. Res.* **2022**, *29*, 27382–27398. [\[CrossRef\]](#)
20. Topping, D.; Bannan, T.J.; Coe, H.; Evans, J.; Jay, C.; Murabito, E.; Robinson, N. Digital Twins of Urban Air Quality: Opportunities and Challenges. *Front. Sustain. Cities* **2021**, *3*, 786563. [\[CrossRef\]](#)
21. Kabir, M.R.; Mila, S.A.; Ray, S. AQUATWIN: A Digital Twin Framework for Early Detection of Water Contamination. In Proceedings of the 2024 4th Interdisciplinary Conference on Electrics and Computer (INTCEC), Chicago, IL, USA, 11 June 2024; IEEE: Piscataway, NJ, USA, 2004; pp. 1–6.
22. Zekri, S.; Jabeur, N.; Gharrad, H. Smart Water Management Using Intelligent Digital Twins. *Comput. Inform.* **2022**, *41*, 135–153. [\[CrossRef\]](#)
23. Hamzah, A.; Aqlan, F.; Baidya, S. Drone-based Digital Twins for Water Quality Monitoring: A Systematic Review. *Digit. Twins Appl.* **2024**, *1*, 131–160. [\[CrossRef\]](#)
24. Peddle, S.D.; Hodgson, R.J.; Borrett, R.J.; Brachmann, S.; Davies, T.C.; Erickson, T.E.; Liddicoat, C.; Muñoz-Rojas, M.; Robinson, J.M.; Watson, C.D.; et al. Practical Applications of Soil Microbiota to Improve Ecosystem Restoration: Current Knowledge and Future Directions. *Biol. Rev.* **2025**, *100*, 1–18. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Tsakiridis, N.L.; Samarinas, N.; Kalopesa, E.; Zalidis, G.C. Cognitive Soil Digital Twin for Monitoring the Soil Ecosystem: A Conceptual Framework. *Soil. Syst.* **2023**, *7*, 88. [\[CrossRef\]](#)
26. Davis, G.B.; Rayner, J.L.; Donn, M.J. Advancing “Autonomous” Sensing and Prediction of the Subsurface Environment: A Review and Exploration of the Challenges for Soil and Groundwater Contamination. *Environ. Sci. Pollut. Res.* **2023**, *30*, 19520–19535. [\[CrossRef\]](#)
27. Bărbulescu, A.; Barbeș, L.; Dumitriu, C. Ștefan Advances in Water, Air and Soil Pollution Monitoring, Modeling and Restoration. *Toxics* **2024**, *12*, 244. [\[CrossRef\]](#)
28. Papageorgiou, A.; Björklund, A.; Sinha, R.; De Almeida, M.L.R.; Steubing, B. Coupling Material and Energy Flow Analysis with Life Cycle Assessment to Support Circular Strategies at the Urban Level. *Int. J. Life Cycle Assess.* **2024**, *29*, 1209–1228. [\[CrossRef\]](#)
29. Geremicca, F.; Fascetti, A.; Brigham, J.C.; Bilec, M.M. Urban Metabolism and Digital Twin Technologies for a Sustainable Built Environment: Towards a Framework for a Campus Application. *IOP Conf. Ser. Earth Environ. Sci.* **2024**, *1363*, 012081. [\[CrossRef\]](#)
30. Borja Pimenta, L.; Beltrão, N.E.S.; De Oliveira, R.M.E.S.; Gomes, D.J.C. Multi-Criteria Decision-Making Methods to Evaluate Urban Environmental Quality: A Scoping Review: Métodos de Tomada de Decisão Multicritério Para Avaliar a Qualidade Ambiental Urbana: Uma Revisão Abrangente. *Concilium* **2024**, *24*, 492–516. [\[CrossRef\]](#)
31. Mackay, B.R.; Shaker, R.R. A Megacities Review: Comparing Indicator-Based Evaluations of Sustainable Development and Urban Resilience. *Sustainability* **2024**, *16*, 8076. [\[CrossRef\]](#)
32. Wandl, A.; Dąbrowski, M.; Berruti, G.; Acke, A.; Obersteg, A.; Varjú, V.; Taelman, S.E.; Arlati, A.; Grodzicka-Kowalczyk, M.; Kowalczyk, M. A Holistic Self-Assessment Tool for Circular Economy Transitions in Cities and Regions. *Eur. XXI* **2024**, *44*, 15–35. [\[CrossRef\]](#)
33. Ogunmakinde, O.E.; Egbelakin, T.; Sher, W. Contributions of the Circular Economy to the UN Sustainable Development Goals through Sustainable Construction. *Resour. Conserv. Recycl.* **2022**, *178*, 106023. [\[CrossRef\]](#)
34. Ginga, C.P.; Ongpeng, J.M.C.; Daly, M.a.K.M. Circular Economy on Construction and Demolition Waste: A Literature Review on Material Recovery and Production. *Materials* **2020**, *13*, 2970. [\[CrossRef\]](#)
35. Gherman, I.-E.; Lakatos, E.-S.; Clinci, S.D.; Lungu, F.; Constandoiu, V.V.; Cioca, L.I.; Rada, E.C. Circularity Outlines in the Construction and Demolition Waste Management: A Literature Review. *Recycling* **2023**, *8*, 69. [\[CrossRef\]](#)
36. Giorgi, S.; Lavagna, M.; Wang, K.; Osmani, M.; Liu, G.; Campioli, A. Drivers and Barriers towards Circular Economy in the Building Sector: Stakeholder Interviews and Analysis of Five European Countries Policies and Practices. *J. Clean. Prod.* **2022**, *336*, 130395. [\[CrossRef\]](#)
37. Coates, A.; Raymond, K. *European Commission Guidance on EIA: Screening*; Office for Official Publications of the European Communities: Luxembourg, 2001; ISBN 978-92-894-1334-3.
38. Helmcke, C. Blind Spots. In *Engineering Reality*; Springer International Publishing: Cham, Switzerland, 2023; pp. 73–95. ISBN 978-3-031-40642-3.

39. Chanchitpricha, C.; Fischer, T.B. The Role of Impact Assessment in the Development of Urban Green Infrastructure: A Review of EIA and SEA Practices in Thailand. *Impact Assess. Proj. Apprais.* **2022**, *40*, 191–201. [\[CrossRef\]](#)
40. Kim, E.-S. Can Data Science Achieve the Ideal of Evidence-Based Decision-Making in Environmental Regulation? *Technol. Soc.* **2024**, *78*, 102615. [\[CrossRef\]](#)
41. Lin, Y.; Zaidi, F. Examining Wildlife Safeguards for Linear Infrastructure Development in India: Bridging Policy and Practice Gaps. *Asian Polit. Policy* **2025**, *17*, e70025. [\[CrossRef\]](#)
42. Blakley, J.; Franks, D. *Handbook of Cumulative Impact Assessment*; Edward Elgar Publishing: Cheltenham, UK, 2021; ISBN 978-1-78347-402-8.
43. Glasson, J.; Durning, B.; Broderick, M.; Welch, K. Monitoring and Auditing the Local Socio-Economic and Environmental Impacts of the Early Stage Construction of Hinkley Point C Nuclear Power Station, UK. *Impact Assess. Proj. Apprais.* **2021**, *39*, 84–95. [\[CrossRef\]](#)
44. Xie, D.; Li, M.; Sun, Q.; He, J. Reinforcement Learning Based Urban Traffic Signal Control and Its Impact Assessment on Environmental Pollution. *E3S Web Conf.* **2024**, *536*, 01021. [\[CrossRef\]](#)
45. Patterson, C.; Casasanta Mostaço, F.; Jaeger, J.A.G. Lack of Consideration of Ecological Connectivity in Canadian Environmental Impact Assessment: Current Practice and Need for Improvement. *Impact Assess. Proj. Apprais.* **2022**, *40*, 481–494. [\[CrossRef\]](#)
46. Rodríguez-Luna, D.; Alcalá, F.J.; Encina-Montoya, F.; Vela, N. The Environmental Impact Assessment of Sanitation Projects in Chile: Overview and Improvement Opportunities Focused on Follow-Ups. *Int. J. Environ. Res. Public Health* **2022**, *19*, 3964. [\[CrossRef\]](#)
47. Butt, A.Q.; Shangguan, D.; Ding, Y.; Banerjee, A.; Sajjad, W.; Mukhtar, M.A. Assessing the Existing Guidelines of Environmental Impact Assessment and Mitigation Measures for Future Hydropower Projects in Pakistan. *Front. Environ. Sci.* **2024**, *11*, 1342953. [\[CrossRef\]](#)
48. Senaratne, S.; Kc, A.; Rai, S. Stakeholder Management Challenges and Strategies for Sustainability Issues in Megaprojects: Case Studies from Australia. *Built Environ. Proj. Asset Manag.* **2024**, *14*, 414–431. [\[CrossRef\]](#)
49. Bhateria, R. EIA Procedure—Mitigation and Impact Management. In *Environmental Impact Assessment*; Springer Nature: Cham, Switzerland, 2024; pp. 47–60. ISBN 978-3-031-66796-1.
50. Pilogallo, A.; Saganeiti, L. Energy Transition and Spatial Transformation: Looking for a Suitable Trade-Off. In *Computational Science and Its Applications, Proceedings of the ICCSA 2023 Workshops, Athens, Greece, 3–6 July 2023*; Gervasi, O., Murgante, B., Rocha, A.M.A.C., Garau, C., Scorza, F., Karaca, Y., Torre, C.M., Eds.; Lecture Notes in Computer Science; Springer Nature: Cham, Switzerland, 2023; Volume 14109, pp. 3–15. ISBN 978-3-031-37119-6.
51. Morrison-Saunders, A.; Arts, J.; Pope, J.; Bond, A.; Retief, F. Distilling Best Practice Principles for Public Participation in Impact Assessment Follow-Up. *Impact Assess. Proj. Apprais.* **2023**, *41*, 48–58. [\[CrossRef\]](#)
52. Onyango, V.; Gazzola, P. Change-Making in Environmental Impact Assessment (EIA): Piloting Changeology Approach Using England as a Case Study. *Impact Assess. Proj. Apprais.* **2024**, *42*, 251–266. [\[CrossRef\]](#)
53. Morrison-Saunders, A.; Arts, J.; Bond, A.; Pope, J.; Retief, F. Reflecting on, and Revising, International Best Practice Principles for EIA Follow-Up. *Environ. Impact Assess. Rev.* **2021**, *89*, 106596. [\[CrossRef\]](#)
54. Mulligan, C.N.; Yong, R.N. Natural Attenuation of Contaminated Soils. *Environ. Int.* **2004**, *30*, 587–601. [\[CrossRef\]](#)
55. Hegglin, M.I. The Self-Cleansing Ability of Prehistoric Air. *Nature* **2017**, *546*, 41–42. [\[CrossRef\]](#)
56. Lelieveld, J.; Dentener, F.J.; Peters, W.; Krol, M.C. Hydroxyl Radicals Maintain the Self-Cleansing Capacity of the Troposphere. *Atmos. Chem. Phys. Discuss.* **2004**, *4*, 3699–3720.
57. Massimi, L.; Ristorini, M.; Simonetti, G.; Frezzini, M.A.; Astolfi, M.L.; Canepari, S. Spatial Mapping and Size Distribution of Oxidative Potential of Particulate Matter Released by Spatially Disaggregated Sources. *Environ. Pollut.* **2020**, *266*, 115271. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Isaksen, I.S.A.; Dalsøren, S.B. Getting a Better Estimate of an Atmospheric Radical. *Science* **2011**, *331*, 38–39. [\[CrossRef\]](#) [\[PubMed\]](#)
59. Harris, N.L.; Gibbs, D.A.; Baccini, A.; Birdsey, R.A.; de Bruin, S.; Farina, M.; Fatoyinbo, L.; Hansen, M.C.; Herold, M.; Houghton, R.A.; et al. Global Maps of Twenty-First Century Forest Carbon Fluxes. *Nat. Clim. Change* **2021**, *11*, 234–240. [\[CrossRef\]](#)
60. GFG. Forest Greenhouse Gas Net Flux. Available online: <https://data.globalforestwatch.org/datasets/gfw::forest-greenhouse-gas-net-flux/explore?location=1.046695%2C0.000000%2C2.00> (accessed on 9 July 2022).
61. Harris, N.; Gibbs, D. Quantifying Carbon Fluxes in the World's Forests. 2021. Available online: <https://www.globalforestwatch.org/blog/climate/forests-carbon-emissions-sink-flux/> (accessed on 10 August 2025).
62. Neinhuis, C. Characterization and Distribution of Water-Repellent, Self-Cleaning Plant Surfaces. *Ann. Bot.* **1997**, *79*, 667–677. [\[CrossRef\]](#)
63. Rabajczyk, A.; Zielecka, M.; Klapsa, W.; Dziechciarz, A. Self-Cleaning Coatings and Surfaces of Modern Building Materials for the Removal of Some Air Pollutants. *Materials* **2021**, *14*, 2161. [\[CrossRef\]](#)

64. Dutta, M.; Reeti, R.; Mandal, S.K. Light Transmitting and Self Cleansing Concrete as a Smart Building Material-a Review. In Proceedings of the 2018 International Conference on Smart City and Emerging Technology (ICSCET), Mumbai, India, 5 January 2018; pp. 1–5.
65. Sarkin, A.S.; Ekren, N.; Sağlam, Ş. A Review of Anti-Reflection and Self-Cleaning Coatings on Photovoltaic Panels. *Sol. Energy* **2020**, *199*, 63–73. [\[CrossRef\]](#)
66. Blossey, R. Self-Cleaning Surfaces—Virtual Realities. *Nat. Mater.* **2003**, *2*, 301–306. [\[CrossRef\]](#)
67. Angelidaki, I.; Sanders, W. Assessment of the Anaerobic Biodegradability of Macropollutants. *Rev. Environ. Sci. Biotechnol.* **2004**, *3*, 117–129. [\[CrossRef\]](#)
68. Bringmann, G.; Kühn, R. Comparison of the Toxicity Thresholds of Water Pollutants to Bacteria, Algae, and Protozoa in the Cell Multiplication Inhibition Test. *Water Res.* **1980**, *14*, 231–241. [\[CrossRef\]](#)
69. Brusseau, M.L.; Guo, B. Revising the EPA Dilution-Attenuation Soil Screening Model for PFAS. *J. Hazard. Mater. Lett.* **2023**, *4*, 100077. [\[CrossRef\]](#)
70. Golovina, E.; Ivanova, I.; Kargashilov, D.; Sushko, E.; Parshina, A. Engineering Environmental Protection at an Industrial Facility. *E3S Web Conf.* **2023**, *381*, 01081. [\[CrossRef\]](#)
71. Ighalo, J.O.; Adeniyi, A.G. Adsorption of Pollutants by Plant Bark Derived Adsorbents: An Empirical Review. *J. Water Process Eng.* **2020**, *35*, 101228. [\[CrossRef\]](#)
72. Fujishima, A.; Zhang, X.; Tryk, D. Heterogeneous Photocatalysis: From Water Photolysis to Applications in Environmental Cleanup. *Int. J. Hydrogen Energy* **2007**, *32*, 2664–2672. [\[CrossRef\]](#)
73. Feng, H.; Hewage, K. Lifecycle Assessment of Living Walls: Air Purification and Energy Performance. *J. Clean. Prod.* **2014**, *69*, 91–99. [\[CrossRef\]](#)
74. González, S.O.; Almeida, C.A.; Calderón, M.; Mallea, M.A.; González, P. Assessment of the Water Self-Purification Capacity on a River Affected by Organic Pollution: Application of Chemometrics in Spatial and Temporal Variations. *Environ. Sci. Pollut. Res.* **2014**, *21*, 10583–10593. [\[CrossRef\]](#)
75. Hammer, D.A. (Ed.) *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural*, 1st ed.; CRC Press: Boca Raton, FL, USA, 1898; ISBN 978-1-00-015767-3.
76. He, W.; Wang, Q.; Zhu, Y.; Wang, K.; Mao, J.; Xue, X.; Shi, Y. Innovative Technology of Municipal Wastewater Treatment for Rapid Sludge Sedimentation and Enhancing Pollutants Removal with Nano-Material. *Bioresour. Technol.* **2021**, *324*, 124675. [\[CrossRef\]](#)
77. He, Y.; Li, L.; Li, J.; Li, W.; Mu, L. Air Purification Efficiency of Thirty Species of Landscape Trees in Northern China. *J. Northeast For. Univ.* **2010**, *38*, 37–39.
78. Iurchenko, V.; Melnikova, O.; Mikhaylova, L.; Lebedeva, E. Contamination and “Self-Cleaning” of Soils, Boarded on the Objects of Automobile and Road Complex, from Petroleum Products. *Procedia Eng.* **2017**, *187*, 783–789. [\[CrossRef\]](#)
79. Karlapudi, A.P.; Venkateswarulu, T.; Tammineedi, J.; Kanumuri, L.; Ravuru, B.K.; Dirisala, V.R.; Kodali, V.P. Role of Biosurfactants in Bioremediation of Oil Pollution-a Review. *Petroleum* **2018**, *4*, 241–249. [\[CrossRef\]](#)
80. Lee, B.X.Y.; Hadibarata, T.; Yuniarto, A. Phytoremediation Mechanisms in Air Pollution Control: A Review. *Water. Air. Soil. Pollut.* **2020**, *231*, 437. [\[CrossRef\]](#)
81. Lu, K.; Guo, S.; Tan, Z.; Wang, H.; Shang, D.; Liu, Y.; Li, X.; Wu, Z.; Hu, M.; Zhang, Y. Exploring Atmospheric Free-Radical Chemistry in China: The Self-Cleansing Capacity and the Formation of Secondary Air Pollution. *Natl. Sci. Rev.* **2019**, *6*, 579–594. [\[CrossRef\]](#) [\[PubMed\]](#)
82. Narain-Ford, D. *Data for “Soil Self-Cleaning Capacity: Removal of Organic Compounds during Sub-Surface Irrigation”*; Utrecht University: Utrecht, The Netherlands, 2022.
83. Ochowiak, M.; Matuszak, M.; Włodarczak, S.; Ancukiewicz, M.; Krupińska, A. The Modified Swirl Sedimentation Tanks for Water Purification. *J. Environ. Manag.* **2017**, *189*, 22–28. [\[CrossRef\]](#) [\[PubMed\]](#)
84. Ostroumov, S.A. On Some Issues of Maintaining Water Quality and Self-Purification. *Water Resour.* **2005**, *32*, 305–313. [\[CrossRef\]](#)
85. Quan, Y.-Y.; Zhang, L.-Z.; Qi, R.-H.; Cai, R.-R. Self-Cleaning of Surfaces: The Role of Surface Wettability and Dust Types. *Sci. Rep.* **2016**, *6*, 38239. [\[CrossRef\]](#)
86. Real, E.; Sartelet, K. Modeling of Photolysis Rates over Europe: Impact on Chemical Gaseous Species and Aerosols. *Atmos. Chem. Phys.* **2011**, *11*, 1711–1727. [\[CrossRef\]](#)
87. Ray, C.; Jasperse, J.; Grischek, T. Bank Filtration as Natural Filtration. In *Drinking Water Treatment*; Ray, C., Jain, R., Eds.; Springer: Dordrecht, The Netherlands, 2011; pp. 93–158. ISBN 978-94-007-1103-7.
88. Tokiwa, Y.; Calabia, B.; Ugwu, C.; Aiba, S. Biodegradability of Plastics. *Int. J. Mol. Sci.* **2009**, *10*, 3722–3742. [\[CrossRef\]](#)
89. Vagnetti, R.; Miana, P.; Fabris, M.; Pavoni, B. Self-Purification Ability of a Resurgence Stream. *Chemosphere* **2003**, *52*, 1781–1795. [\[CrossRef\]](#)
90. Vieira, J.; Matos, P.; Mexia, T.; Silva, P.; Lopes, N.; Freitas, C.; Correia, O.; Santos-Reis, M.; Branquinho, C.; Pinho, P. Green Spaces Are Not All the Same for the Provision of Air Purification and Climate Regulation Services: The Case of Urban Parks. *Environ. Res.* **2018**, *160*, 306–313. [\[CrossRef\]](#)

91. Yu, C.-H.; Huang, C.-H.; Tan, C.-S. A Review of CO₂ Capture by Absorption and Adsorption. *Aerosol Air Qual. Res.* **2012**, *12*, 745–769. [\[CrossRef\]](#)
92. Yu, C.; Sasic, S.; Liu, K.; Salameh, S.; Ras, R.H.A.; van Ommen, J.R. Nature-Inspired Self-Cleaning Surfaces: Mechanisms, Modelling, and Manufacturing. *Chem. Eng. Res. Des.* **2020**, *155*, 48–65. [\[CrossRef\]](#)
93. Xing, Y.; Brimblecombe, P. Role of Vegetation in Deposition and Dispersion of Air Pollution in Urban Parks. *Atmos. Environ.* **2019**, *201*, 73–83. [\[CrossRef\]](#)
94. Xing, J.; Huang, J.; Wang, X.; Yang, F.; Bai, Y.; Li, S.; Zhang, X. Removal of Low-Concentration Tetracycline from Water by a Two-Step Process of Adsorption Enrichment and Photocatalytic Regeneration. *J. Environ. Manag.* **2023**, *343*, 118210. [\[CrossRef\]](#)
95. Wang, X.; An, Y.; Zhang, J.; Shi, X.; Zhu, C.; Li, R.; Zhu, M.; Chen, S. Contribution of Biological Processes to Self-Purification of Water with Respect to Petroleum Hydrocarbon Associated with No. 0 Diesel in Changjiang Estuary and Jiaozhou Bay, China. *Hydrobiologia* **2002**, *469*, 179–191. [\[CrossRef\]](#)
96. Weyens, N.; Thijs, S.; Popek, R.; Witters, N.; Przybysz, A.; Espenshade, J.; Gawronska, H.; Vangronsveld, J.; Gawronski, S. The Role of Plant–Microbe Interactions and Their Exploitation for Phytoremediation of Air Pollutants. *Int. J. Mol. Sci.* **2015**, *16*, 25576–25604. [\[CrossRef\]](#)
97. Wei, G.; Yang, Z.; Cui, B.; Li, B.; Chen, H.; Bai, J.; Dong, S. Impact of Dam Construction on Water Quality and Water Self-Purification Capacity of the Lancang River, China. *Water Resour. Manag.* **2009**, *23*, 1763–1780. [\[CrossRef\]](#)
98. Zachara, J.M.; Ainsworth, C.C.; Cowan, C.E.; Resch, C.T. Adsorption of Chromate by Subsurface Soil Horizons. *Soil Sci. Soc. Am. J.* **1989**, *53*, 418–428. [\[CrossRef\]](#)
99. Zhao, M.M.; Chen, Y.; Xue, L.; Fan, T.T. Three Kinds of Ammonia Oxidizing Microorganisms Play an Important Role in Ammonia Nitrogen Self-Purification in the Yellow River. *Chemosphere* **2020**, *243*, 125405. [\[CrossRef\]](#)
100. Spellerberg, I.F. *Monitoring Ecological Change*, 2nd ed.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2005; ISBN 978-0-521-82028-8.
101. Hastings, A. Timescales, Dynamics, and Ecological Understanding. *Ecology* **2010**, *91*, 3471–3480. [\[CrossRef\]](#)
102. European Commission. *Joint Research Centre. Development of the EU Sustainable Finance Taxonomy: A Framework for Defining Substantial Contribution for Environmental Objectives 3–6*; Publications Office: Luxembourg, 2022.
103. Ball-Damerow, J.E.; Brenskelle, L.; Barve, N.; Soltis, P.S.; Sierwald, P.; Bieler, R.; LaFrance, R.; Ariño, A.H.; Guralnick, R.P. Research Applications of Primary Biodiversity Databases in the Digital Age. *PLoS ONE* **2019**, *14*, e0215794. [\[CrossRef\]](#)
104. Feng, X.; Enquist, B.J.; Park, D.S.; Boyle, B.; Breshears, D.D.; Gallagher, R.V.; Lien, A.; Newman, E.A.; Burger, J.R.; Maitner, B.S.; et al. A Review of the Heterogeneous Landscape of Biodiversity Databases: Opportunities and Challenges for a Synthesized Biodiversity Knowledge Base. *Glob. Ecol. Biogeogr.* **2022**, *31*, 1242–1260. [\[CrossRef\]](#)
105. Tang, L.; Ruan, J.; Bo, X.; Mi, Z.; Wang, S.; Dong, G.; Davis, S.J. Plant-Level Real-Time Monitoring Data Reveal Substantial Abatement Potential of Air Pollution and CO₂ in China’s Cement Sector. *One Earth* **2022**, *5*, 892–906. [\[CrossRef\]](#)
106. Cao, K.; Liu, Y.; Meng, G.; Sun, Q. An Overview on Edge Computing Research. *IEEE Access* **2020**, *8*, 85714–85728. [\[CrossRef\]](#)
107. *ISO 14064-1:2018; Greenhouse Gases—Part 1: Specification with Guidance at the Organization Level for Quantification and Reporting of Greenhouse Gas Emissions and Removals*. ISO: Geneva, Switzerland, 2018.
108. *ISO 14001:2015; Environmental Management Systems. Requirements with Guidance for Use*. International Organization for Standardization: Geneva, Switzerland, 2015.
109. Bennett, N.J.; Whitty, T.S.; Finkbeiner, E.; Pittman, J.; Bassett, H.; Gelcich, S.; Allison, E.H. Environmental Stewardship: A Conceptual Review and Analytical Framework. *Environ. Manag.* **2018**, *61*, 597–614. [\[CrossRef\]](#)
110. OECD. *The Circular Economy in Cities and Regions: Synthesis Report*; OECD Urban Studies; OECD: Paris, France, 2020; ISBN 978-92-64-64295-9.
111. Ferreira, A.; Pinheiro, M.D.; Brito, J.D.; Mateus, R. A Critical Analysis of LEED, BREEAM and DGNB as Sustainability Assessment Methods for Retail Buildings. *J. Build. Eng.* **2023**, *66*, 105825. [\[CrossRef\]](#)
112. Omer, M.A.B.; Noguchi, T. A Conceptual Framework for Understanding the Contribution of Building Materials in the Achievement of Sustainable Development Goals (SDGs). *Sustain. Cities Soc.* **2020**, *52*, 101869. [\[CrossRef\]](#)
113. Cleveland, C.J.; Ruth, M. Indicators of Dematerialization and the Materials Intensity of Use. *J. Ind. Ecol.* **1998**, *2*, 15–50. [\[CrossRef\]](#)
114. Huang, B.; Gao, X.; Xu, X.; Song, J.; Geng, Y.; Sarkis, J.; Fishman, T.; Kua, H.; Nakatani, J. A Life Cycle Thinking Framework to Mitigate the Environmental Impact of Building Materials. *One Earth* **2020**, *3*, 564–573. [\[CrossRef\]](#)
115. Gómez-Gil, M.; Sesana, M.M.; Salvalai, G.; Espinosa-Fernández, A.; López-Mesa, B. The Digital Building Logbook as a Gateway Linked to Existing National Data Sources: The Cases of Spain and Italy. *J. Build. Eng.* **2023**, *63*, 105461. [\[CrossRef\]](#)
116. Liu, G.; Chen, R.; Xu, P.; Fu, Y.; Mao, C.; Hong, J. Real-Time Carbon Emission Monitoring in Prefabricated Construction. *Autom. Constr.* **2020**, *110*, 102945. [\[CrossRef\]](#)
117. Aslam, M.S.; Huang, B.; Cui, L. Review of Construction and Demolition Waste Management in China and USA. *J. Environ. Manag.* **2020**, *264*, 110445. [\[CrossRef\]](#)

118. Saravanan, A.; Senthil Kumar, P.; Jeevanantham, S.; Karishma, S.; Tajsabreen, B.; Yaashikaa, P.R.; Reshma, B. Effective Water/Wastewater Treatment Methodologies for Toxic Pollutants Removal: Processes and Applications towards Sustainable Development. *Chemosphere* **2021**, *280*, 130595. [\[CrossRef\]](#)
119. Satyam, S.; Patra, S. Innovations and Challenges in Adsorption-Based Wastewater Remediation: A Comprehensive Review. *Heliyon* **2024**, *10*, e29573. [\[CrossRef\]](#)
120. Chen, L.; Huang, L.; Hua, J.; Chen, Z.; Wei, L.; Osman, A.I.; Fawzy, S.; Rooney, D.W.; Dong, L.; Yap, P.-S. Green Construction for Low-Carbon Cities: A Review. *Environ. Chem. Lett.* **2023**, *21*, 1627–1657. [\[CrossRef\]](#)
121. Fei, W.; Opoku, A.; Agyekum, K.; Oppon, J.A.; Ahmed, V.; Chen, C.; Lok, K.L. The Critical Role of the Construction Industry in Achieving the Sustainable Development Goals (SDGs): Delivering Projects for the Common Good. *Sustainability* **2021**, *13*, 9112. [\[CrossRef\]](#)
122. Pichette, G.; Blanchet, P.; Essoua Essoua, G.G.; Breton, C. Environmental Product Declaration (EPD) Usage in Early Building Design Stages: Review of Effects on the Environmental Life Cycle of a Multi-Residential Building. *BioResources* **2023**, *18*, 8134–8150. [\[CrossRef\]](#)
123. Debele, S.E.; Leo, L.S.; Kumar, P.; Sahani, J.; Ommer, J.; Bucchignani, E.; Vranić, S.; Kalas, M.; Amirzada, Z.; Pavlova, I.; et al. Nature-Based Solutions Can Help Reduce the Impact of Natural Hazards: A Global Analysis of NBS Case Studies. *Sci. Total Environ.* **2023**, *902*, 165824. [\[CrossRef\]](#)
124. Cheng, J.C.P.; Ma, L.Y.H. A BIM-Based System for Demolition and Renovation Waste Estimation and Planning. *Waste Manag.* **2013**, *33*, 1539–1551. [\[CrossRef\]](#)
125. Bogue, R. Design for Disassembly: A Critical Twenty-first Century Discipline. *Assem. Autom.* **2007**, *27*, 285–289. [\[CrossRef\]](#)
126. Durmisevic, E.; Guerriero, A.; Boje, C.; Domange, B.; Bosch, G. Development of a Conceptual Digital Deconstruction Platform with Integrated Reversible BIM to Aid Decision Making and Facilitate a Circular Economy. In Proceedings of the Joint Conference CIB W78-LDAC, Luxembourg, 11–15 October 2021; p. 10.
127. Lin, T.; Lin, Y.; Ren, H.; Chen, H.; Chen, Q.; Li, Z. Development and Key Technologies of Pure Electric Construction Machinery. *Renew. Sustain. Energy Rev.* **2020**, *132*, 110080. [\[CrossRef\]](#)
128. Gharbia, M.; Chang-Richards, A.; Lu, Y.; Zhong, R.Y.; Li, H. Robotic Technologies for On-Site Building Construction: A Systematic Review. *J. Build. Eng.* **2020**, *32*, 101584. [\[CrossRef\]](#)
129. Konya, A.; Nematzadeh, P. Recent Applications of AI to Environmental Disciplines: A Review. *Sci. Total Environ.* **2024**, *906*, 167705. [\[CrossRef\]](#)
130. Nakanishi, Y.; Kaneta, T.; Nishino, S. A Review of Monitoring Construction Equipment in Support of Construction Project Management. *Front. Built Environ.* **2022**, *7*, 632593. [\[CrossRef\]](#)
131. Verma, R.; Singh, B.K.; Zahidi, F. Management of GPS Tracking Systems in Transportation. In *Intelligent Transportation System and Advanced Technology*; Upadhyay, R.K., Sharma, S.K., Kumar, V., Eds.; Energy, Environment, and Sustainability; Springer Nature: Singapore, 2024; pp. 251–263. ISBN 978-981-9705-14-6.
132. Zhang, C.; Hu, M.; Di Maio, F.; Sprecher, B.; Yang, X.; Tukker, A. An Overview of the Waste Hierarchy Framework for Analyzing the Circularity in Construction and Demolition Waste Management in Europe. *Sci. Total Environ.* **2022**, *803*, 149892. [\[CrossRef\]](#)
133. Scaife, A.D. Improve Predictive Maintenance through the Application of Artificial Intelligence: A Systematic Review. *Results Eng.* **2024**, *21*, 101645. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.