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Life cycle assessment as a decision-making tool for sustainable engineering in U.S: Methods, standards, and industrial applications

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Abstract

Life Cycle Assessment (LCA) has evolved from a static environmental accounting tool into an increasingly important decision-support tool for sustainable engineering. In the United States, its relevance has expanded alongside industrial decarbonization targets, circular economy strategies, and rising demand for transparent environmental product evaluation. This review synthesizes recent peer-reviewed literature on methodological advances, standardization, and industrial applications of LCA, with emphasis on developments that strengthen its practical role in engineering decisions. Attention is given to digital innovations such as machine learning, sensor-enabled inventory generation, dynamic and prospective modeling, and integration with complementary decision tools. Across sectors, the literature demonstrates that LCA is most influential when introduced early in design and planning, where it supports trade-off analysis among environmental, economic, and performance objectives. Evidence from construction, transportation, aerospace, and manufacturing indicates that methodological sophistication is expanding faster than institutional adoption, largely because data quality, scenario assumptions, and reporting consistency remain uneven. Emerging standards, including the International Organization for Standardization ISO 14075, further indicate a shift toward broader sustainability assessment that includes social dimensions. We conclude that recent developments suggest that LCA is becoming a strategic tool for engineering decisions. However, wider impact will depend on stronger data harmonization, methodological transparency, and improved integration into routine professional practice. This review also identifies gaps that must be addressed for LCA to support broader sustainability goals.

Keywords: Life Cycle Assessment; Sustainability; Decision-Making; Industrial Applications; Circular Economy; LCA

1. Introduction

Sustainable engineering has increasingly moved from being a specialized environmental concern to a core requirement in industrial planning, infrastructure development, and technology design (Glavič, 2022). This shift has been accelerated by global climate targets, decarbonization strategies, corporate disclosure requirements, and mounting demands to account for resource depletion, emissions intensity, and material circularity across complete production systems (Johnsson et al., 2020). Engineering decisions are now expected to address not only technical performance and economic feasibility but also long-term environmental consequences (Ashen et al., 2025). Across sectors such as construction, manufacturing, transport, and energy, this requires that decision makers consider impacts that extend beyond immediate project boundaries. These expanded responsibilities have increased demand for analytical frameworks capable of evaluating environmental consequences across entire supply chains rather than only at the point of production or use.

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This has made life cycle thinking central to sustainable engineering. Life cycle thinking is a structured framework that examines a product's entire lifespan, from production to consumption (Huang et al., 2020). Within this framework, Life Cycle Assessment (LCA) remains the most widely established analytical method. LCA is a standardized methodology for quantifying the environmental impacts of products, processes, or systems (Schenk and Amiri, 2022; Kleinekorte et al., 2020). By encompassing raw material acquisition, production, use, and disposal, LCA provides a comprehensive cradle-to-grave perspective on resource use and emissions (Annankra and Sefa-Boateng, 2025).

Furthermore, this full-spectrum view enables environmental impacts to be assessed under defined functional units and system boundaries. The LCA method reveals trade-offs (e.g., material and energy impacts) and improves consistency when comparing alternatives that are invisible in siloed analyses (Bajdur et al., 2024). A material substitution may improve operational performance while increasing embodied emissions. Similarly, technologies promoted as low-carbon may depend on energy-intensive extraction or difficult disposal pathways. By capturing impacts across all stages, LCA helps identify where environmental hotspots occur before major design decisions become fixed (Pryshlakivsky and Searcy, 2021).

In essence, LCA has gained importance amid policy goals for decarbonization and the circular economy. Engineering sectors that contribute substantially to global emissions are expected to justify design and procurement choices through quantified environmental evidence (Felicioni et al., 2025). In the built environment, for example, operational energy improvements have gradually shifted attention toward embodied emissions because material production now constitutes a larger share of total life cycle impacts in efficient buildings. This has increased the use of LCA in evaluating structural systems, low-carbon materials, and construction alternatives before implementation (Penchev et al., 2025).

The methodological foundation of LCA has been well established in ISO 14040/14044 (2006) standards, with periodic revisions. The 2020 editions reaffirm LCA's role as "methodology of choice" for environmental assessment (Enking et al., 2025). Modern LCA studies still adhere to these principles, but contemporary research is pushing beyond traditional, static assessments (Enking et al., 2025). Recent trends include dynamic and prospective LCA that integrate future scenarios, the use of digital data streams for life cycle inventory (LCI) and coupling LCA with other sustainability metrics (Nurdiawati et al., 2025; Piron et al., 2024; Salati et al., 2024). These advances reflect a shift from retrospective accounting toward real-time, data-driven decision support.

Despite its potential, the integration of LCA is often uneven in practical decision-making. These include limitations in life-cycle inventory data quality, weak institutional feedback mechanisms linking environmental impact results to decision processes, and difficulties in harmonizing methodological standards across industries. A study also highlights that the presence of LCA results does not automatically guarantee influence on engineering or management decisions. Managerial factors such as organizational behavior and cognitive biases can hinder the uptake of LCA findings (Pryshlakivsky and Searcy, 2021).

While case studies document LCA results for specific products or sectors, there is a need for a synthetic overview that identifies how recent methodological developments, institutional standards, and sectoral practices shape the role of LCA in sustainable engineering. This review addresses that by examining current advances in methods, standards, and industrial applications, with attention to how LCA is positioned within engineering decision processes. The objective is to provide an updated foundation for understanding how LCA is evolving, where methodological tensions remain, and what this implies for future sustainability-oriented engineering practice.

2. Review methodology

This paper adopts a narrative review approach to synthesize recent developments in life cycle assessment relevant to sustainable engineering and decision-making in the United States. Peer-reviewed journal articles published primarily between 2020 and 2026 were prioritized to capture contemporary methodological and application trends. Literature was identified through academic databases, such as Web of Science and Google Scholar, with a focus on studies addressing methodological innovation, digital integration, standards development, and industrial applications.

The review prioritized literature from construction, transportation, manufacturing, and infrastructure, where LCA informs engineering decisions. Rather than following a systematic screening protocol, the analysis focused on identifying recurring themes, methodological shifts, and interpretative patterns across recent studies. Comparative synthesis was used to examine the transition of LCA from an environmental reporting framework into a broader decision-support tool across industrial contexts.

3. Advancements in life cycle assessment and digital integration

3.1. Data-Driven and Digital Innovations In LCA

A major trend is the digitalization of LCA data collection and analysis. Industry 4.0 technologies, such as the Internet of Things (IoT), cyber-physical systems, and real-time sensors, are being explored to enrich the life cycle inventory (LCI) with dynamic process data (Wang, 2025; Piron et al., 2024). Piron et al., (2024) systematically evaluated how specific Industry 4.0 technologies can be applied to each stage of LCI compilation, finding that IoT, simulation tools, and cyber-physical systems are particularly effective in automating data capture. These technologies promise to reduce reliance on static databases like U.S. LCI or Ecoinvent by enabling continuous monitoring of manufacturing processes. For example, sensor networks on a production line could feed real-time material and energy use into LCA models, improving accuracy.

Machine learning (ML) and artificial intelligence (AI) are also being integrated into LCA workflows. Wang (2025) reveals recent work suggesting that ML can help fill data gaps, harmonize heterogeneous datasets, and even predict environmental impacts from minimal inputs. Techniques such as natural language processing are used to parse literature and automate scope definition, while regression and surrogate modeling accelerate impact calculations. For instance, ML-based predictive models match traditional LCA simulations for ship emissions when calibrated with operational data (Wang, 2025). Altogether, ML can make LCA more adaptable and timelier, though it introduces challenges of model transparency and validation.

Digital twins, which are virtual replicas of physical products or systems, offer another frontier. By coupling digital twins with dynamic LCA models, engineers can simulate future scenarios and optimize design in real time. In a related study, Raut et al., (2025) developed an integrated predictive-LCA framework for additive manufacturing, using Gaussian Process models to incorporate live sensor data and uncertainties into the LCA outputs. The result was a dynamic LCA, where decision criteria (cost, emissions, durability) are adaptively weighted. This integration significantly improves predictive accuracy and optimizes materials in real time. Such approaches illustrate how emerging tools can overcome the static nature of conventional LCA models (Petri et al., 2025).

These digital trends are enhancing LCA by making inventory data more granular and updatable. They address long-standing issues of data gaps and uncertainty. However, they also demand new expertise and raise questions about data quality control and standardization. Tools that integrate IoT and ML must still align with established LCA standards, and practitioners will need guidance to ensure that automated data remains verifiable.

3.2. Methodological advancements: dynamic, prospective, and integrated life cycle assessment

Two key methodological developments are dynamic/prospective LCA, together with the integration of other decision analysis frameworks. Traditional LCA typically treats systems as static snapshots, but real engineering decisions often hinge on future changes in technology, markets, or infrastructure (Nurdiawati et al., 2025; Salati et al., 2024).

Dynamic LCA accounts for temporal variations (such as grid decarbonization or technology learning curves) when assessing the life-cycle impacts of systems. Salati et al., 2024 highlight dynamic LCA for buildings, pointing out that factors like time-dependent energy emissions and material aging often significantly affect the outcomes, yet are frequently overlooked in conventional studies. These dynamic approaches allow LCA to support long-term planning decisions with greater realism (Salati et al., 2024).

Meanwhile, prospective LCA (pLCA) is gaining traction for emerging technologies. Prospective LCA (pLCA) explicitly models future scenarios or technological scenarios (e.g., decarbonized infrastructure, new fuel pathways) and their environmental impacts. In Nurdiawati et al., (2025), the study reviews prospective LCA and highlights that incorporating decarbonization scenarios (e.g., changes in the energy mix or material supply) can drastically alter LCA results compared to static models (Nurdiawati et al., 2025). This stresses the importance of scenario development with uncertainties to produce meaningful, forward-looking LCA results.

An additional methodological innovation is the integration of LCA with other analyses to form hybrid decision frameworks. Life Cycle Cost Analysis (LCCA) is one of the most common partners: by combining LCA's environmental metrics with LCCA's economic metrics, engineers can evaluate both eco-performance and cost (Felicioni et al., 2025). For instance, BEES (Building for Environmental and Economic Sustainability) software merges EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) LCA impacts with net present value calculations, enabling the comparison of building materials on both environmental and financial grounds.

More complex integrations use Multi-Criteria Decision Analysis (MCDA). Wang, (2025) describes machine learning (ML)-driven MCDA models that predict life-cycle impacts (e.g., CO_2, energy) and optimize design choices under uncertainty. In additive manufacturing, Raut et al. (2025) achieved 85-90% accuracy in predictive LCA by coupling Gaussian Process models with MCDA to optimize material and process parameters (Raut et al., 2025). These studies depict that LCA is becoming a component of larger optimization frameworks, rather than a standalone spreadsheet. These innovations make LCA more actionable as decision-makers can explore trade-offs (e.g., cost and impact) and account for uncertainties, thereby making LCA results directly relevant to real-world choices.

3.3. Standards, guidelines, and frameworks

Standardization remains a cornerstone for credible LCA practice. The core ISO 14040/14044 frameworks remain the baseline for environmental LCA, but we see recent expansions. Specifically, ISO 14067 (2018) standardizes product carbon footprints, while the recent ISO 14075:2024 extends LCA principles to Social Life Cycle Assessment (S-LCA) (Traverso et al., 2025). This new standard fills a critical gap and formalizes how to consider social indicators (labor conditions, community impacts) in life-cycle studies (Traverso et al., 2025). This milestone reflects the trend toward Life Cycle Sustainability Assessment (LCSA), which integrates environmental LCA with life cycle costing (LCC) and social LCA (Firoozi et al., 2025). Although LCSA frameworks (ISO 14008, ISO 15686-5) exist, they are still less developed and rarely used in practice.

Meanwhile, regulatory and institutional developments in the United States are increasingly shaping how life cycle assessment is implemented beyond the core ISO framework. The U.S. Environmental Protection Agency (EPA) has published guidelines on life cycle inventories through platforms such as LCA Commons (Jelse and Peerens, 2018). This is to improve consistency in background datasets and methodological transparency for U.S. analysts, particularly in environmental reporting and comparative assessments for Environmental Product Declarations (EPDs).

In parallel, ASTM International (formerly American Society for Testing and Materials) continues to refine sector-relevant standards, including ASTM E2150-17(2024), which provides a standardized classification framework for life-cycle environmental work elements and cost structures across environmental projects, helping align inventory development and reporting practices across applied engineering contexts. These institutional efforts are important because they translate broad ISO comparability principles into formats that are operationally usable within national industries and procurement systems. Recent academic evidence supports this, Firoozi et al., (2025) applied LCA with standardized functional units in civil infrastructure, finding that digital integration and sector-specific databases substantially improve impact accuracy in civil infrastructure LCA, where project boundaries and data sources are otherwise inconsistent (Firoozi et al., 2025).

Beyond technical inventories, reporting frameworks, such as the Greenhouse Gas Protocol Product Standard, connect LCA outputs to corporate disclosure systems and climate target mechanisms. The impacts of LCA are also related to sustainability frameworks like the Sustainable Development Goals (SDGs) and corporate reporting (e.g., the Carbon Disclosure Project (CDP) and Science Based Target initiative (SBTi), underscoring its importance in modern engineering practices (Firoozi et al., 2025). Despite its significance, methodological harmonization remains incomplete because organizational priorities, interpretive choices, and reporting assumptions still influence how results are used in practice. The findings from Pryshlakivsky and Searcy, (2021) indicate that the decision-support value of LCA depends not only on formal standards but also on transparency, institutional trust, and consistent interpretation across users (Traverso et al., 2025; Pryshlakivsky and Searcy, 2021).

Standards are evolving to cover broader aspects of life cycle impacts (ISO 14075 for social metrics) and to provide sector-specific guidance. In practice, U.S. engineers may draw on both international norms and local guidelines. The trend is toward greater harmonization and transparency, but variability in methodologies (allocation rules, system boundaries, impact categories) still leads to uncertainty. Explicit criteria in Product Category Rules (PCRs) or ISO standards and consistency in databases will improve comparability so that decision-makers can interpret LCA appropriately.

3.4. Sectoral applications of life cycle assessment

3.4.1. Construction and Infrastructure: LCA for Trade-off Analysis and Evaluating Alternatives

In the construction sector, life cycle assessment has become especially influential because major environmental consequences are often locked in during early design decisions. During the early stages of construction, material systems, structural alternatives, and service-life assumptions are still flexible. Recent studies therefore show that LCA is most valuable when integrated upstream with design tools rather than applied after material selection has already been finalized. Felicioni et al., (2025) integrated LCA with building information modeling (BIM) and life-cycle costing for a public building project. It was demonstrated that adding LCA early allowed trade-off analysis of design choices. More broadly, Firoozi et al., (2025) further applied LCA case studies to civil projects and reported that combining advanced digital tools such as BIM and Geographic Information Systems (GIS) and sector-specific data improved impact assessment accuracy. An LCA review by Schenk and Amiri (2022) also claimed that timber buildings typically have lower embodied energy than steel/concrete buildings. These findings support trends such as adopting mass timber or low-carbon concrete.

Similarly, in pavement engineering, this same early-decision role is evident in comparisons between warm-mix and conventional asphalt systems. A research study implemented LCA to evaluate alternative mixes like Warm Mix Asphalt vs Hot Mix Asphalt and recycled materials, assess fuel use, emissions, and durability trade-offs (Afshin and Behnood, 2025). The studies generally indicate that warm-mix technologies reduce fuel use and GHGs in production, but the net benefit depends on context (additive type, haul distances, structural performance). This explains why recent pavement research increasingly links LCA with environmental product declarations and procurement criteria, allowing agencies such as the Federal Highway Administration to use verified life-cycle data in material selection and infrastructure sustainability programs.

3.4.2. Transportation: LCA for Carbon Footprint Reduction

In the automotive and aerospace sectors, LCA helps compare technology pathways, material choices, and fuel-related emissions. Penchev et al., (2025) utilized LCA and the life-cycle global warming potential of 7-8 battery-electric trucks in California yielded approximately 75% lower well-to-wheel CO_2-equivalent emissions than diesel trucks, underscoring the role of LCA in guiding fleet decarbonization and grid planning (notably, BEV benefits were sensitive to the U.S. grid mix).

In the aerospace industry, Hasan et al., (2025) performed a cradle-to-grave LCA of passenger seat frames. They discovered that seat frames composed of steel had life-cycle GHG emissions of approximately 208 kt CO_2 equivalent, whereas magnesium frames were only roughly 44.9 kt CO_2 equivalent per functional unit. This stark difference (steel >4× higher than magnesium) illustrates how LCA can pinpoint material substitutions for lighter, lower-emission aircraft components. Such sectoral studies guide engineers on which technology or material changes yield the greatest sustainability gains.

3.4.3. Manufacturing and Process Industries

In the manufacturing sector, LCA is widely used for material design and supply chain decisions. Raut et al., (2025) coupled LCA with machine learning and optimization techniques in the additive manufacturing sector, where they demonstrated high predictive accuracy while reducing material waste and cost. Public-sector programs also leverage LCA through the EPA's Environmentally Preferable Purchasing (EPP) initiative, which has developed simplified LCA tools to help buyers choose "greener" products. For example, life-cycle studies of U.S. produced goods often integrate country-specific inventory data (US LCI), enabling more accurate footprint comparisons for domestic and imported materials. The general trend is that manufacturing LCA tends to focus on guiding incremental product innovation and supply chain management, rather than infrastructure-level planning (Bhat et al., 2021). Nevertheless, these case studies collectively demonstrate LCA's versatility from redesigning a product component to large-scale strategic decisions (e.g., national fuel policy).

3.5. Circular economy and life cycle sustainability assessment

A growing research direction links LCA with circular economy (CE) principles and broader sustainability assessment. Many engineering programs now connect LCA to resource recovery and material efficiency initiatives. LCA's holistic perspective naturally complements circular design thinking by quantifying the benefits of reuse, recycling, and waste avoidance. Recent reviews emphasize using LCA to evaluate circular strategies (Heidak et al., 2025; Schwarz et al., 2024). However, circularity (i.e., increased recycling) does not automatically imply environmental benefit unless assessed against a linear baseline. In other words, LCA helps ensure that CE actions truly reduce overall impacts. This nexus of LCA and CE is gaining research focus, as evidenced by recent reviews and the proliferation of EPDs for recycled-content products

Moreover, the concept of Life Cycle Sustainability Assessment (LCSA) seeks to integrate environmental LCA with life cycle costing and social LCA. Traverso et al., (2025) indicates that although ISO standards exist for each pillar, application of full LCSA remains rare and methodologically challenging. Some pilot studies (Virgolino and Holden, 2026; Dunuwila et al., 2025) attempt to link LCA results to social impact indicators or UN Sustainable Development Goals. The benefits are clear: LCA combined with social metrics can inform more equitable sustainability decisions. This includes assessing labor conditions or community impacts alongside carbon footprints. However, data for social indicators is often sparse, and standard practice is still evolving.

Embedding LCA within CE and LCSA paradigms reflects a shift from narrow environmental metrics to a triple-bottom-line view. The new ISO 14075 for S-LCA is a signal of momentum in this direction (Traverso et al., 2025). For engineers, this means that future LCA will likely include cost and social dimensions. Achieving this will require cross-disciplinary tools and consensus on metrics. Nonetheless, these integrative approaches align with industry and policy demands for comprehensive sustainability performance (ESG reporting).

4. Discussion

4.1. From Static Accounting to Adaptive Decision Intelligence in Life Cycle Assessment

A major trend across recent LCA literature is the movement from retrospective environmental accounting toward adaptive decision support. Earlier LCA applications primarily served to quantify impacts after system design, but current approaches support decisions during design and operational stages (Kleinekorte et al., 2020). This transition is largely driven by digital tools that improve how inventory data are generated, updated, and interpreted in near real time (Piron et al., 2024). Across sectors, machine learning (ML) and sensor-based systems are reducing dependence on fixed background datasets and making assessments more responsive to process variability (Petri et al., 2025; Wang, 2025). These developments make LCA more responsive, but they also introduce new concerns about model transparency and interpretation when automated methods are used. This means that future credibility will depend not only on predictive power but also on explainability and traceability of digital LCA outputs.

4.2. Dynamic and Prospective LCA for Long-Term Engineering Decisions

Dynamic and prospective approaches reflect an expanding recognition that many engineering decisions depend on future system changes rather than present-day conditions alone. Conventional models assume stable background systems, yet this assumption is seemingly difficult to justify in sectors shaped by temporal variations, material innovation, and policy uncertainty (Salati et al., 2024). Across applications, considering future scenarios improves the ability of LCA to capture how environmental burdens shift as infrastructure, technologies, and supply chains evolve (Nurdiawati et al., 2025). This explains why prospective LCA is becoming more central in innovation-oriented research than in conventional product comparison studies. Yet prospective methods also introduce a challenge of scenario credibility, since assumptions about future policy, energy supply, or market adoption strongly influence results. Therefore, while dynamic and prospective LCA improve realism, they also require stronger justification of assumptions than conventional environmental assessments.

4.3. Expansion of Standards Outpaces Methodological Convergence

The continued expansion of LCA standards indicates strong institutional commitment, but practical convergence across methods remains incomplete. International Organization for Standardization standards cover broader sustainability dimensions, including social impacts through ISO 14075, reflecting the movement toward more integrated life cycle thinking (Traverso et al., 2025). Yet across sectors, comparable studies still differ because system boundaries, allocation choices, and database selection remain uneven (Firoozi et al., 2025). This suggests that formal standardization alone does not eliminate interpretive variability in applied LCA. In agreement with Pryshlakivsky and Searcy, (2021), methodological credibility steadily depends on transparent reporting that allows users to understand why technically valid studies may still produce different conclusions.

4.4. Sectoral Applications Reveal Different Levels of Decision Influence

Across construction, transportation, aerospace, and manufacturing, LCA is most influential when it is embedded early enough to shape design choices rather than used only for post-assessment reporting. Construction applications echo LCA's emphasis on comparing alternative material systems, making integration with life cycle costing especially important (Felicioni et al., 2025). In the transportation and aerospace sector, performance efficiency and material selection are closely linked. LCA often directly informs engineering trade-offs by identifying where environmental gains align with operational improvements (Hasan et al., 2025; Penchev et al., 2025). Manufacturing occupies an intermediate position, where LCA continuously supports process optimization because environmental performance can be adjusted alongside production efficiency (Raut et al., 2025). This suggests that sectoral differences are defined less by whether LCA is applied and more by the stage at which it enters decision-making and the type of trade-off it is expected to resolve.

4.5. Circular Economy Benefits Require Full Life-Cycle Verification

The developing connection between LCA and circular economy has expanded the role of environmental assessment from measuring impacts to testing sustainability claims. Circular strategies often assume that reuse, recycling, or material recovery automatically reduce burdens, yet recent studies suggest that these outcomes remain highly dependent on system conditions (Schwarz et al., 2024). Across sectors, LCA increasingly functions as a verification tool that distinguishes resource efficiency from actual environmental improvement. This is important because circular interventions can reduce burdens in one life-cycle stage while increasing them elsewhere. As a result, LCA is becoming central not only to evaluating circular options but also to preventing simplified interpretations of circularity in engineering practice.

5. Future directions and research gaps

Notwithstanding the significant progress, several gaps and challenges remain. Addressing these gaps will deepen the decision-making potential of LCA for sustainable engineering:

5.1. Data and Inventory Gaps

Despite recent advances, data limitations remain one of the most persistent barriers, especially for emerging materials, chemicals, or new technologies. Hence, prospective LCI databases (pLCI) are needed to model future technologies (Nurdiawati et al., 2025). Spatial and temporal coverage across various industries is also limited, ignoring location-specific factors like transport distances that reduce uncertainty in LCA (Salati et al., 2024).

5.2. Standardization and Comparability

While standards exist, methodological inconsistencies persist. Allocation of multi-output processes, choice of impact metrics, and boundary selection can vary widely between studies, limiting the comparability of LCA results. Greater harmonization of industry-specific guidelines (PCRs), sectoral databases, and mandated transparency can help. Novel LCA approaches sometimes sidestep issues of uncertainty and can undermine consistent decision support (Pryshlakivsky and Searcy, 2021). Future work should aim for agreed conventions (within sectors or regulatory frameworks) and tools that clarify methodological choices to users.

5.3. Broadening Impact Scope

Current LCAs and life-cycle costing mostly focus on environmental impacts (climate, resources, pollution) while social and economic aspects are lagging. Even though ISO 14075 now provides guidance for S-LCA, very few studies incorporate labor conditions, health, or equity (Traverso et al., 2025). Future research should test comprehensive LCSA approaches, quantifying, for example, how material choices affect both emissions and social outcomes. Connecting LCA to sustainability indices (SDGs, ESG metrics) is another frontier.

5.4. Policy and Regulatory Integration

Although standardization efforts (PCRs, environmental product declarations) are steps forward, enforceable policy using LCA (such as carbon pricing or sustainable procurement) is still nascent. Future research should explore how LCA results can be translated into actionable policy levers (setting building codes based on LCA thresholds). Collaboration between scientists, industry, and regulators will be crucial to closing this loop.

6. Conclusion

In closing, this review demonstrates that Life Cycle Assessment is no longer used only to quantify environmental burdens but progressively to structure engineering decisions under multiple sustainability constraints. Across this reviewed literature, the most significant development is not simply methodological refinement, but the growing ability of LCA to connect environmental evidence with practical choices involving materials, processes, and long-term system performance. The comparison across sectors emphasizes that its decision value depends largely on how early assessment enters project planning and how effectively results are combined with economic and operational criteria. At the same time, the literature suggests that methodological sophistication alone does not guarantee wider influence, particularly where data quality and interpretability remain uneven. Looking ahead, future progress will depend on making LCA outputs more comparable, decision-oriented, and adaptable to emerging technological systems, especially as sustainability expectations increasingly demand evidence that extends beyond single-impact environmental reporting.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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