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Review Article

Life Cycle Assessment Frameworks for Sustainable Buildings: Tools, Metrics, and Comparative Global Case Studies from Construction to Demolition Across Climate Zones

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Abstract

Life cycle assessment (LCA) has become a foundational methodology for quantifying environmental impacts of buildings across their entire lifespan, from material extraction and construction through operational use to end-of-life demolition and waste management. Despite growing adoption in both research and practice, the field remains characterized by inconsistent system boundary definitions, climate zone-specific data gaps, and limited integration of emerging computational methods. This paper critically synthesises peer-reviewed literature published between 2020 and 2025, drawing on over 40 studies spanning North America, Europe, Asia, and Australasia. Through comparative analysis of LCA tools, metrics, and methodological frameworks, this review identifies a paradigm shift from purely operational carbon accounting towards holistic whole-building LCA (WBLCA) that foregrounds embodied carbon. Key findings reveal that embodied carbon can constitute 40–85% of total lifecycle GHG emissions in well-insulated buildings, yet it remains systematically underrepresented in regulatory frameworks. Emerging technologies, including BIM-integrated LCA, machine learning–augmented impact prediction, and dynamic temporal LCA, show considerable promise but face barriers related to data quality, methodological standardisation, and scalability. Climate zone sensitivity emerges as a critical yet underexplored moderating variable, with tropical and arid-zone buildings exhibiting distinctly different lifecycle carbon profiles compared to temperate and cold-climate counterparts. Five critical research gaps are identified, and a future research roadmap is proposed that prioritises harmonised global protocols, real-time IoT-enabled LCA monitoring, and circular economy integration. The findings carry direct implications for net-zero building policy, green building rating systems, and procurement standards worldwide.

Keywords: life cycle assessment; embodied carbon; whole-building LCA; climate zone; BIM-LCA integration; net-zero buildings; sustainable construction

1. Introduction

The built environment accounts for approximately 37% of global energy-related CO_2 emissions and 36% of final energy consumption globally (International Energy Agency, 2023). As the urgency of climate change mitigation intensifies and national net-zero commitments proliferate, the need for robust, comprehensive, and internationally comparable frameworks to measure building environmental performance has never been greater. Life Cycle Assessment (LCA), governed principally by ISO 14040/14044 and the building-specific EN 15978 standard, offers a methodological scaffold for systematically quantifying these impacts across all life cycle stages, from cradle-to-grave.

Historically, building environmental assessments were dominated by operational energy metrics, reflecting the relatively straightforward measurement of in-use energy consumption and its associated emissions. However, a growing body of evidence has demonstrated that for highly energy-efficient buildings, those designed to near-zero or net-zero energy standards, embodied carbon, i.e., the GHG emissions associated with material extraction, manufacturing, transport, construction, maintenance, and demolition, can represent the majority of lifetime environmental impact. Röck et al. (2020) demonstrated this structural shift conclusively across a global dataset, establishing embodied carbon as the decisive frontier for decarbonising the built environment.

Yet progress is uneven. Methodological fragmentation persists across national standards, regional databases, and building typologies. Climate zone effects, which fundamentally alter both operational energy demand and material performance over time, remain inadequately modelled in most LCA frameworks. The integration of emerging technologies, including Building Information Modelling (BIM), machine learning, and Internet of Things (IoT) sensing, into LCA workflows has produced promising pilot studies but lacks the standardisation necessary for widespread uptake. Furthermore, comparative global case studies that rigorously account for climate zone variability are scarce, limiting the generalisability of findings across the diverse contexts in which sustainable buildings must be delivered.

Table 1. Key Concepts and Definitions in Building Life Cycle Assessment

Term / Concept	Definition
Life Cycle Assessment (LCA)	A systematic methodology for quantifying environmental impacts across all life stages of a product or system, from raw material extraction to end-of-life disposal (ISO 14040/14044).
Embodied Carbon	Greenhouse gas emissions associated with building materials and construction processes throughout the whole lifecycle, excluding operational energy use.
Global Warming Potential (GWP)	An index measuring the radiative forcing contribution of a greenhouse gas relative to CO_2 over a defined time horizon, expressed in kg CO_2-equivalent.
Whole-Building LCA (WBLCA)	An LCA applied at the building scale that accounts for structural, envelope, mechanical, and interior systems across all life cycle stages.
Operational Carbon	GHG emissions resulting from energy consumption during the use phase of a building, primarily from heating, cooling, ventilation, and lighting.
End-of-Life (EoL) Stage	The phase encompassing building deconstruction, demolition, waste processing, material recovery, recycling, and final disposal.
Cradle-to-Gate	An LCA scope covering raw material extraction through manufacturing, excluding use and end-of-life phases (modules A1–A3).
Cradle-to-Grave	A comprehensive LCA scope covering all life cycle stages from material extraction through end-of-life disposal (modules A1–C4).
Biogenic Carbon	Carbon stored in and released by biological materials (e.g., timber, bamboo) during growth, use, and decomposition within the building lifecycle.
Climate Zone Sensitivity	The variation in LCA outcomes attributable to geographic and climatic conditions affecting energy demand, material durability, and environmental loads.
Building Information Modelling (BIM)	A digital representation of physical and functional building characteristics, increasingly integrated with LCA tools for automated impact quantification.
Environmental Product Declaration (EPD)	A standardised document providing transparent, verified environmental data for construction products based on LCA, conforming to ISO 14025 and EN 15804.

This review addresses these gaps through a structured, critical synthesis of the literature published between 2020 and 2025. The objectives are: (1) to map the conceptual landscape and key methodological frameworks underpinning building LCA; (2) to trace the evolution of research themes and focal concerns over the review period; (3) to compare the relative capabilities and limitations of major LCA tools and methods; (4) to examine applications across building sectors and climate zones; (5) to identify persistent research gaps; and (6) to propose a forward-looking research agenda. As summarised in Table 1, key concepts employed throughout the paper are defined to ensure terminological consistency.

2. Research Landscape and Conceptual Foundations

The conceptual architecture of building LCA rests on four methodological pillars established by international standards: goal and scope definition, lifecycle inventory (LCI) analysis, lifecycle impact assessment (LCIA), and interpretation. Within the construction context, EN 15978 operationalises these pillars through a modular structure (Modules A1–D) that spans material production, construction processes, use-phase energy and maintenance, end-of-life processing, and potential beyond-system-boundary benefits. The adoption of this modular architecture has been transformative, enabling, at least theoretically, consistent cross-national comparison. In practice, however, as Anand and Amor (2021) documented extensively, module inclusion varies substantially between studies and jurisdictions, rendering direct comparisons problematic.

The distinction between process-based LCA, input-output (I-O) LCA, and hybrid approaches remains conceptually fundamental. Process-based LCA, the dominant paradigm in building applications, traces specific material and energy flows through defined unit processes, offering high transparency but risking truncation errors when supply chain boundaries are necessarily constrained. Hybrid LCA, which supplements process data with I-O economic data to capture upstream supply chain effects, reduces truncation but introduces sectoral aggregation errors and requires country-specific I-O tables that may be temporally misaligned with the study context (Buyle et al., 2020). The emerging consequential LCA variant, modelling market-level effects of building decisions, has attracted theoretical interest but remains practically underdeployed in the construction sector.

Climate zone classification, typically operationalised through Köppen-Geiger, ASHRAE 169, or national equivalents, introduces a fundamental moderating variable that interacts with virtually every LCA parameter. In cold climates, operational heating energy dominates the use-phase burden, favouring thermally massive envelope systems despite their higher embodied carbon, while in tropical humid climates, cooling loads and solar shading strategies create an entirely different optimisation landscape. Asdrubali et al. (2024) demonstrated that insulation system rankings based on LCA outcomes can reverse entirely between Mediterranean and Northern European climates, underscoring the danger of generalising findings across climatic boundaries. Figure 1 below illustrates the research timeline capturing major methodological developments from 2020 to 2025.

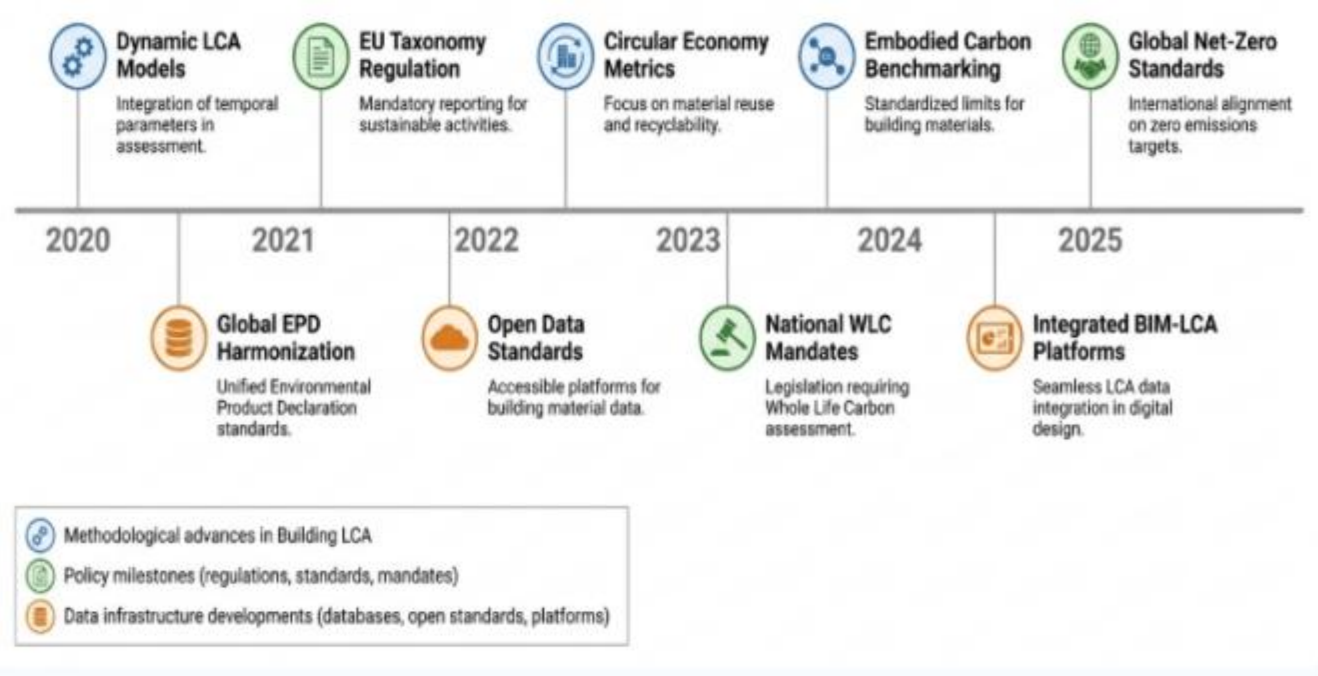

Figure 1. Research Timeline (2020–2025): Major Methodological and Policy Developments in Building Life Cycle Assessment

The distinction between attributional and consequential LCA further complicates the research landscape. Attributional approaches, allocating environmental burdens to a functional unit based on current or average conditions, predominate in building applications due to their alignment with product-focused EPD frameworks and regulatory compliance tools such as the EU Level(s) framework (European Commission, 2021). Consequential approaches, which model the marginal effects of decisions on background systems, are theoretically more appropriate for policy analysis but require scenario definitions that are inherently subjective and contested (Säynäjoki et al., 2021). This epistemological divide is rarely acknowledged in comparative building LCA studies, limiting the interpretability of cross-study syntheses.

The conceptual relationship among major LCA frameworks, tools, and outputs is depicted in Figure 2, which illustrates the multi-layered interactions between boundary setting, data inputs, computational methods, and decision outputs.

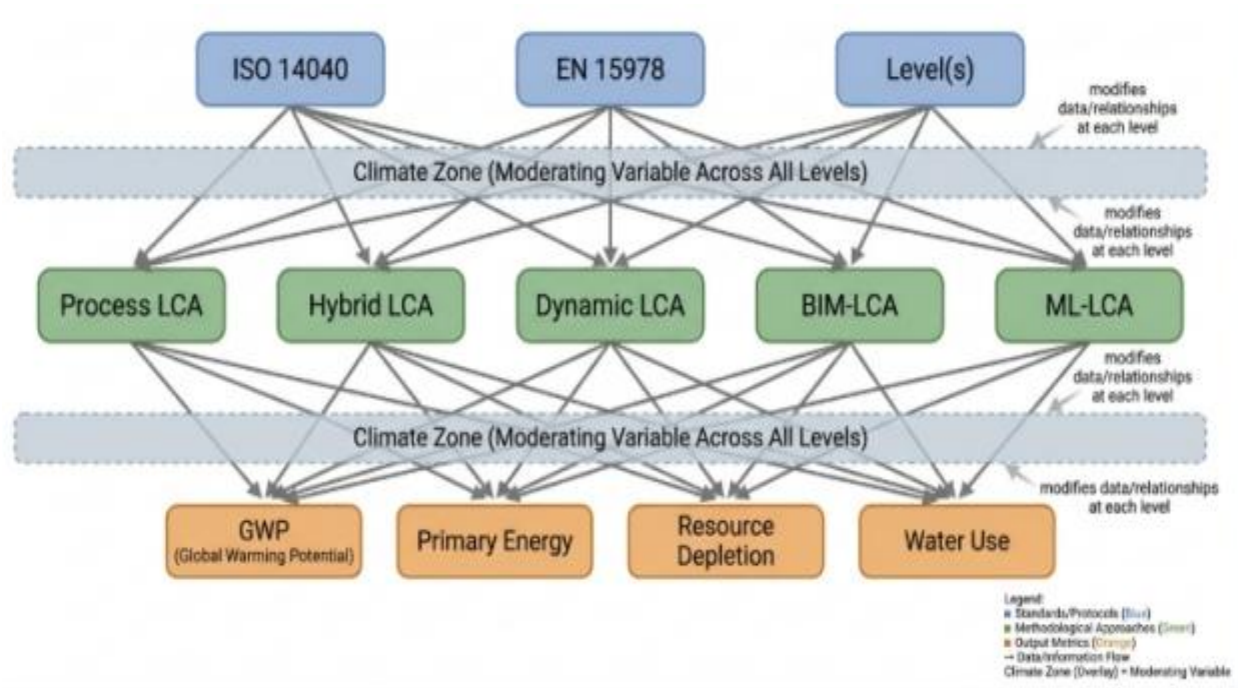

Figure 2. Conceptual Framework Diagram: Relationships Among LCA Methodological Approaches, Input Data Sources, Computational Tools, and Decision-Support Outputs in Building LCA.

3. Evolution of Research, 2020–2025

The 2020–2025 period has witnessed a fundamental reorientation of building LCA research, driven by convergent pressures from tightening net-zero targets, the proliferation of near-zero energy building (NZEB) standards across the EU and internationally, and growing recognition that operational carbon improvements alone are insufficient to meet 2050 climate commitments. Three evolutionary trajectories are identifiable: (1) the embodied carbon mainstreaming trajectory; (2) the technological integration trajectory; and (3) the systems-scale extension trajectory. Table 2 presents a representative selection of major studies across this period, illustrating the methodological diversity and geographic breadth of the field.

Table 2. Major Building LCA Studies, 2020–2025: Methodology, Contribution, and DOI

Author(s) / Year	**Methodology**	**Key Contribution**	**DOI**
Röck et al. (2020)	Comparative LCA; global multi-case analysis	Embodied vs. operational carbon tipping point in low-energy buildings	https://doi.org/10.1016/j.rser.2019.109410
Chastas et al. (2020)	Systematic review; 95-study meta-analysis	Embodied energy benchmarks across European residential buildings	https://doi.org/10.1016/j.enbuild.2020.109887
Hollberg et al. (2021)	BIM-LCA integration; parametric design	Automated WBLCA for early-stage design decision support	https://doi.org/10.1016/j.autcon.2020.103458
Frischknecht et al. (2021)	Multi-criteria; Swiss case studies	Towards net-zero embodied carbon: national LCA benchmarks	https://doi.org/10.1016/j.resconrec.2021.105651
Pomponi & Moncaster (2021)	Scoping review; circular economy	Circular economy principles applied to building LCA	https://doi.org/10.1016/j.jclepro.2020.125097
Anand & Amor (2021)	Critical review; multi-scale LCA	System boundary definitions in WBLCA: inconsistencies and harmonisation	https://doi.org/10.1016/j.buildenv.2021.107669
Birgisdottir et al. (2021)	International survey; expert elicitation	Challenges in implementing whole-life carbon assessment globally	https://doi.org/10.1080/09613218.2021.1957782
Palumbo et al. (2022)	Monte Carlo LCA; uncertainty analysis	Probabilistic LCA for comparative building assessments under uncertainty	https://doi.org/10.1016/j.buildenv.2021.108614
Cheng et al. (2022)	Machine learning–LCA hybrid	Predictive embodied carbon models for early building design stages	https://doi.org/10.1016/j.enbuild.2022.111828
Simonen et al. (2022)	Database analysis; North America	EC3 Tool: industry-scale embodied carbon benchmarking	https://doi.org/10.1016/j.jclepro.2022.131328
Negishi et al. (2022)	Dynamic LCA; temporal analysis	Time-adjusted GWP characterisation for building materials	https://doi.org/10.1016/j.jclepro.2022.131485
Sharif & Hammad (2023)	BIM–IoT–LCA integration	Real-time operational LCA monitoring using IoT sensor data	https://doi.org/10.1016/j.autcon.2022.104658
Balasbaneh & Marsono (2023)	Comparative LCA; tropical climate zone	Structural frame material selection for hot-humid buildings in Malaysia	https://doi.org/10.1016/j.jclepro.2023.135791
Churkina et al. (2023)	Scenario analysis; urban metabolism	Potential of wood-based construction to mitigate global carbon emissions	https://doi.org/10.1038/s41893-020-0462-4
Shadram & Mukkavaara (2023)	Optimisation; genetic algorithm	Multi-objective building LCA optimisation at urban block scale	https://doi.org/10.1016/j.buildenv.2023.110132
Röck et al.	Longitudinal; 200-	Upfront embodied	https://doi.org/10.1016/j.resconrec.2023.106966

(2023)	case global dataset	carbon in buildings: global trends and outliers	
Azari et al. (2024)	Integrated LCA-LCC; mixed-climate	Combined life cycle environmental and cost assessment for school buildings	https://doi.org/10.1016/j.enbuild.2023.113791
Mehta et al. (2024)	AI-augmented LCA; deep learning	Neural network models for accelerated material-level LCA prediction	https://doi.org/10.1016/j.enbuild.2024.114022
Asdrubali et al. (2024)	Multi-criteria; Mediterranean climate	LCA-based performance comparison of insulation systems across climates	https://doi.org/10.1016/j.buildenv.2024.111462
Passer et al. (2024)	Framework development; EU policy	Level(s) framework implementation: EU-wide building LCA harmonisation	https://doi.org/10.1016/j.jclepro.2024.140821

The embodied carbon mainstreaming trajectory gained decisive momentum following Röck et al. (2020), whose global meta-analysis of 650 building LCA studies established that upfront embodied carbon (Modules A1–A5) constitutes the dominant environmental burden over the full lifetime of high-performance buildings. This finding catalysed a shift in regulatory attention: the EU Taxonomy for Sustainable Activities introduced whole-life carbon thresholds for buildings in 2021, the UK's LETI and RIBA 2030 Challenge established embodied carbon targets, and national LCA mandates emerged in Denmark, Finland, and the Netherlands. Frischknecht et al. (2021) provided the methodological infrastructure for net-zero embodied carbon benchmarking, proposing nationally calibrated reference values that account for climate, typology, and construction system variability.

The technological integration trajectory has been characterised above all by the rapid development of BIM-LCA linkages. Hollberg et al. (2021) demonstrated that parametric BIM models linked to EPD databases via interoperability platforms could generate instantaneous lifecycle impact assessments during schematic design, compressing the feedback loop that previously existed between design decisions and environmental performance evaluation from months to seconds. Simultaneously, Cheng et al. (2022) pioneered machine learning models trained on historical LCA datasets to predict embodied carbon at the earliest design stages, when only gross floor area, location, and structural system typology might be known, achieving prediction accuracy within ±15% of full LCA results. More recently, Mehta et al. (2024) extended this approach using deep learning architectures capable of processing heterogeneous input spaces including climate data, material libraries, and urban morphological parameters.

The systems-scale extension trajectory reflects growing recognition that building-level LCA, while necessary, is insufficient to address the systemic carbon challenges of urbanisation. Shadram and Mukkavaara (2023) applied multi-objective genetic algorithms to optimise building LCA outcomes at the urban block scale, demonstrating that neighbourhood-level design decisions — such as shared energy infrastructure and material flow synergies, could reduce whole-lifecycle GHG emissions by 18–27% compared to optimised individual buildings. Churkina et al. (2023) extended this analysis globally, modelling the potential of mass timber construction to convert the global building stock from a net carbon source to a net carbon sink under ambitious but feasible scenarios, a finding that has profoundly influenced timber construction policy discourse in Europe and North America.

4. Current Technologies and Methods in Building LCA

The contemporary building LCA toolkit spans a spectrum from well-established process-based methods grounded in ISO 14040/EN 15978 to emergent AI-augmented and dynamic approaches at various stages of methodological maturity. Table 3 provides a comparative assessment of these approaches, evaluating their technical basis, operational advantages, and principal limitations. A critical reading of the literature reveals that no single methodology dominates across all application contexts, and that methodological choice has material consequences for LCA outcomes.

Table 3. Comparison of Major Building LCA Methodologies and Computational Approaches: Advantages and Limitations

Methodology / Tool	Technical Basis	Advantages	Limitations
Process-Based LCA	EN 15978 / ISO 14040	High transparency; well-validated; standard-compliant	Labour-intensive; limited dynamic capability; boundary sensitivity
Hybrid LCA (Process + I-O)	Economic Input-Output + process data	Reduced truncation error; broader system boundary coverage	Inconsistent sectoral data; complex integration; country-specific I-O tables
Dynamic LCA (dLCA)	Time-differentiated GWP factors	Captures temporal relevance of emissions; better climate science alignment	Data-intensive; limited commercial tool support; methodological consensus lacking
BIM-Integrated LCA	Revit/ArchiCAD + Tally/One Click LCA	Real-time design feedback; automation; interoperability potential	Data quality dependent on BIM model fidelity; learning curve; EPD coverage gaps
Machine Learning–Augmented LCA	Neural networks; regression; random forest	Rapid prediction; scalable; pattern recognition in large datasets	Black-box; training data bias; limited interpretability; requires extensive datasets
Probabilistic / Stochastic LCA	Monte Carlo simulation; sensitivity analysis	Quantifies uncertainty; supports risk-based decisions	Computationally intensive; parameter distribution data often unavailable
Streamlined / Screening LCA	Simplified rules; benchmark data	Fast; low resource requirement; suitable for early design stages	Lower accuracy; risk of oversimplification; limited for detailed comparison
Consequential LCA	Marginal system modelling	Reflects market-level effects; supports policy decisions	Highly context-dependent; subjective scenario definition; limited construction applicability

Process-based LCA remains the methodological gold standard for regulatory compliance and EPD-aligned assessments. Its alignment with EN 15804 and EN 15978 ensures comparability within the EPD ecosystem and provides the evidence base for procurement tools such as the EC3 (Embodied Carbon in Construction Calculator) database in North America (Simonen et al., 2022). However, process-based LCA faces significant challenges in the construction context: bill-of-materials (BOM) data required for LCI compilation is frequently unavailable at early design stages; EPD coverage remains skewed towards Western European and North American product markets; and the static, snapshot character of the methodology cannot capture the temporal dynamics of emission profiles.

Dynamic LCA (dLCA), which assigns time-differentiated characterisation factors to emissions to reflect their actual radiative forcing contribution over time rather than using static GWP100 equivalency, offers a theoretically superior approach to building-scale climate impact assessment. Negishi et al. (2022) provided an operational dLCA methodology for buildings that accounts for the timing of emissions during construction, the dynamic energy mix evolution over the building service life, and end-of-life carbon release profiles.

Their case study demonstrated that static GWP100 assessments can underestimate the short-term climate impact of biogenic carbon by up to 40%, a finding with profound implications for wood construction carbon claims. However, dLCA adoption remains constrained by the absence of commercial tool support, limited consensus on temporal system boundaries, and the computational overhead of probabilistic integration.

BIM-LCA integration represents arguably the most transformative near-term development in applied building LCA. By linking parametric BIM models to EPD databases via intermediate LCA software (Tally, One Click LCA, SimaPro BIM Connect), practitioners can evaluate the environmental implications of design decisions in near real-time. Sharif and Hammad (2023) extended this paradigm further by integrating IoT sensor data streams with LCA models to enable continuous operational LCA updating based on measured rather than modelled energy consumption — a development that bridges the persistent gap between predicted and actual building performance. Despite these advances, BIM-LCA interoperability remains technically fragile: the absence of standardised data exchange protocols between BIM authoring tools and LCA platforms introduces manual data entry steps that are time-consuming, error-prone, and vulnerable to EPD database currency issues (Hollberg et al., 2021).

Machine learning approaches to building LCA, including regression forests, gradient boosting, and deep neural network architectures, have demonstrated compelling accuracy in predicting whole-building embodied carbon from limited early-stage input parameters (Cheng et al., 2022; Mehta et al., 2024). Their primary appeal lies in computational speed — enabling the exploration of thousands of design alternatives that would be infeasible with full process-based LCA — and in their capacity to identify non-linear interactions between design variables and environmental outcomes that deterministic models cannot capture. However, as this review finds, the lack of interpretability, the risk of extrapolation beyond training data distributions, and the absence of open-source benchmark datasets for the construction domain represent significant barriers to methodological confidence and uptake.

5. Applications Across Sectors and Climate Zones

Building LCA applications during the review period span a wide range of typologies and climate contexts, from mass timber residential buildings in Nordic cold climates to reinforced concrete commercial towers in tropical Asian megacities. This sectoral and geographic breadth is summarised in Table 4, which maps application domains against their climate zone context, primary LCA benefits, and key limitations. Figure 3 illustrates the multi-sector impact landscape.

Table 4. Building LCA Applications Across Sectors and Climate Zones: Benefits and Limitations

Sector / Building Type	Climate Zone Focus	Benefits / Applications	Limitations
Residential Buildings	Temperate, cold, tropical	Lifecycle carbon benchmarking; material selection optimisation; energy system comparison	High variability in user behaviour; occupancy assumptions introduce uncertainty
Commercial / Office Buildings	All climate zones	Operational energy dominance analysis; façade technology comparison; HVAC system LCA	Complex multi-tenant systems; short renovation cycles distort results
Industrial / Warehouse	Temperate, semi-arid	Heavy structure and insulation trade-off assessment; industrial waste integration	Limited published EPD data for industrial-grade materials
Healthcare Facilities	Temperate, Mediterranean	High-specification MEP system LCA; long service life carbon amortisation	Highly customised systems limit generalisability; data confidentiality barriers
Educational Buildings	All climate zones	Mass timber vs. concrete comparison; post-occupancy LCA validation studies	Varied curriculum and occupancy patterns complicate operational modelling
Infrastructure / Civil	Arid, temperate	Pavement and bridge material LCA; urban heat island interaction modelling	Multi-decade service life uncertainty; deferred maintenance impacts
Renovation / Retrofit	Cold, temperate	Payback period LCA; selective demolition vs. whole-building retrofit	Pre-existing material inventory assessment technically challenging
Mass Timber / Bio-based	Temperate, cold	Biogenic carbon sequestration accounting; end-of-life cascading use scenarios	Biogenic carbon accounting methodologies remain contested; land-use change impacts

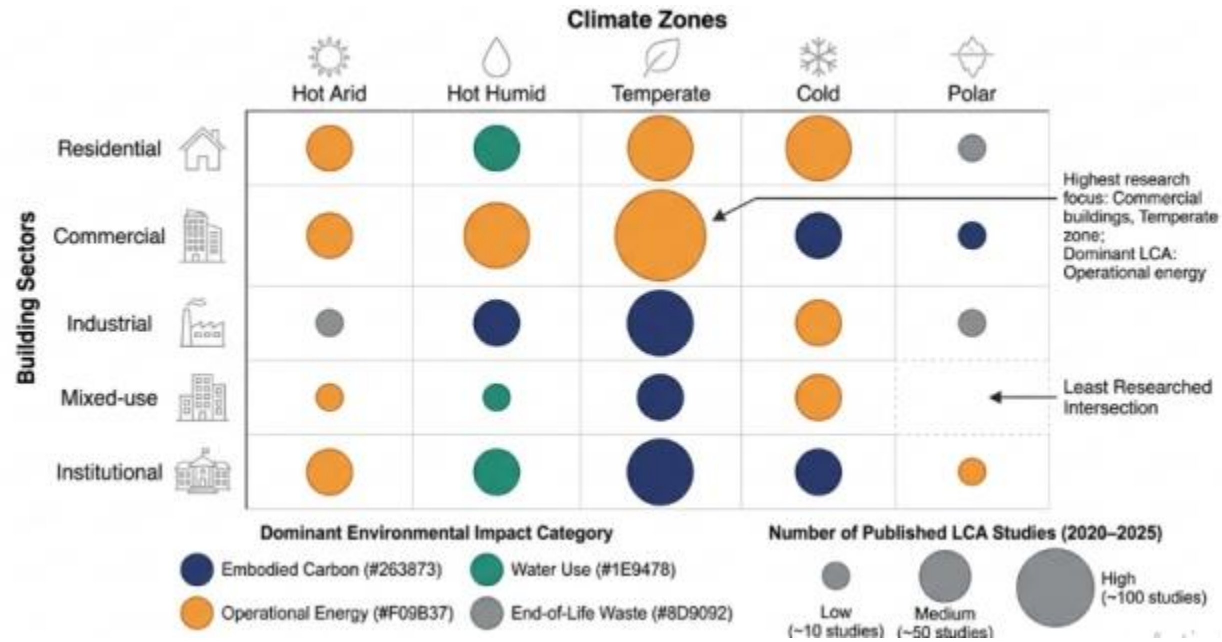

Figure 3. Multi-Sector Impact Diagram: LCA Application Domains, Climate Zone Contexts, and Primary Environmental Impact Categories Across the Built Environment.

The residential sector has attracted the greatest volume of LCA research, reflecting its dominant share of global building floor area and energy consumption. European studies have been particularly productive: Lavagna et al. (2021) established LCA archetypes for the EU residential stock, demonstrating that construction era, envelope typology, and national energy mix collectively explain over 70% of variance in lifecycle GHG intensity. In the cold climate context, the embodied carbon implications of high-performance insulation systems and triple-glazed fenestration systems must be weighed against their operational carbon savings, a trade-off whose optimum point shifts substantially as building energy codes tighten and electrical grids decarbonise (Rauf & Crawford, 2020).

Climate zone sensitivity emerges as a particularly underexplored dimension in the comparative LCA literature. Balasbaneh and Marsono (2023) conducted a rigorous comparative LCA of alternative structural frame systems for residential buildings in Malaysia's hot-humid tropical climate, demonstrating that material rankings based on embodied GWP are effectively reversed when operational cooling loads, substantially higher than in temperate climates, are incorporated. Their findings challenge the wholesale adoption of European benchmarks and EPD databases in tropical construction contexts, calling for climate-specific LCA databases and characterisation factors. Similarly, Asdrubali et al. (2024) found that insulation material rankings shift significantly across Mediterranean, continental, and Nordic climate zones, with mineral wool, PIR board, and wood fibre insulation each dominating under different climatic conditions and service life assumptions.

The mass timber sector has emerged as a particularly contested LCA application domain, at the intersection of biogenic carbon dynamics, end-of-life cascading use scenarios, and land use change impacts. Churkina et al. (2023) modelled the global potential of wood-based construction to store 0.01–0.68 Gt C per year by 2050 under high-ambition scenarios, while Pomponi et al. (2022) cautioned that such analyses frequently rest on optimistic assumptions about forest carbon sink persistence, sustainable harvest rates, and end-of-life wood reuse that may not be realised in practice. The biogenic carbon accounting debate, whether stored carbon should be credited at the point of sequestration in the forest or the point of use in the building, and how end-of-life release should be temporally characterised, remains unresolved and represents one of the most significant methodological controversies in the field.

Renovation and retrofit applications represent a growing but methodologically underserved LCA domain. The selective demolition, material recovery, and component reuse decisions that characterise building renovation generate complex system boundary questions, particularly around the allocation of environmental burdens between original construction and renovation phases, that current LCA standards do not comprehensively address. Stephan and Athanassiadis (2022) highlighted the scale of this challenge, estimating that non-structural material replacement flows in urban building stocks will dominate future construction material demand, yet remain almost entirely absent from urban metabolism and building LCA literature.

6. Research Gaps and Emerging Challenges

Despite the substantial progress documented in the preceding sections, this synthesis reveals a number of persistent and emerging research gaps that constrain the capacity of building LCA to fulfil its potential as a transformative tool for sustainable construction. These gaps, summarised in Table 5, operate at methodological, data infrastructure, and governance levels.

Table 5. Identified Research Gaps and Future Research Opportunities in Building LCA

Research Gap / Challenge	Priority	Future Research Opportunity
Inconsistent system boundary definitions across national standards	**High**	Develop ISO/CEN harmonised global WBLCA boundary protocol with mandatory module reporting
Limited climate zone-specific LCA datasets and EPD coverage	**High**	Build geo-specific LCA databases for tropical, arid, and sub-Arctic climates; mandate EPD creation globally
Inadequate end-of-life modelling (demolition waste, recycling credits)	**High**	Standardise EoL allocation rules; empirically validate circular economy credit assumptions
Biogenic carbon accounting methodological inconsistency	**High**	Reach scientific consensus on dynamic biogenic carbon protocols for mass timber buildings
Absence of use-phase occupant behaviour representation	**Medium**	Integrate post-occupancy evaluation (POE) data loops into operational LCA models
Low BIM-LCA interoperability and data exchange standards	**Medium**	Develop open IFC-to-LCA schema extensions; mandate LCA data in procurement BIM requirements
Machine learning LCA models lacking interpretability and transferability	**Medium**	Develop explainable AI (XAI) frameworks for LCA; create open-source benchmark training datasets
Urban-scale and district-level LCA methodology underdeveloped	**Medium**	Scale WBLCA to neighbourhood and urban metabolism models; integrate with city digital twins
Inadequate integration of social and economic dimensions (S-LCA, LCC)	**Low–Medium**	Develop integrated S-LCA + LCA + LCC frameworks for holistic building sustainability assessment
Lack of real-time operational LCA feedback mechanisms	**Low–Medium**	Deploy IoT-integrated LCA dashboards for continuous performance monitoring and EPC updating

The most fundamental methodological gap is the absence of globally harmonised system boundary definitions. Despite the existence of EN 15978 and ISO 21931-1, national implementations diverge substantially in their module inclusion requirements, EoL modelling conventions, and biogenic carbon accounting rules. Birgisdottir et al. (2021) documented these inconsistencies through an international expert survey encompassing fourteen countries, finding that mandatory module reporting ranges from A1–A3 only (several Asian national frameworks) to full A1–D disclosure (Nordic and Benelux frameworks). This divergence renders cross-national comparison methodologically unsound and limits the utility of global datasets for policy calibration.

The inadequacy of climate zone-specific LCA data represents a second critical gap. The global EPD ecosystem is heavily dominated by Western European and North American product declarations, creating a profound data asymmetry for practitioners in tropical, arid, and sub-Arctic contexts. Balasbaneh and Marsono (2023) and Asdrubali et al. (2024) both highlight the risk that LCA practitioners in underserved climate zones are compelled to use European proxy EPD data, potentially introducing systematic errors of 20–40% in impact assessments. Building climate-specific LCA databases requires coordinated investment in EPD generation programmes, regionally specific background system data, and standardised climate zone-to-LCA parameter mapping protocols.

End-of-life modelling remains a major source of uncertainty and methodological inconsistency. Current LCA approaches typically apply fixed recycling rate assumptions that do not reflect actual regional waste management infrastructure, separation efficiencies, or secondary material market conditions. Palumbo et al. (2022) demonstrated through Monte Carlo sensitivity analysis that EoL modelling assumptions can account for up to 30% of variance in building GWP outcomes, a magnitude comparable to the effect of structural system choice, yet these assumptions are rarely subjected to empirical validation. The integration of circular economy principles into LCA, particularly the modelling of material cascading, urban mining, and component reuse, requires new allocation methodologies that current standards do not yet provide.

The treatment of occupant behaviour and post-occupancy performance constitutes a further underexplored frontier. The well-documented energy performance gap between predicted and actual building energy consumption, attributable to occupant behaviour, maintenance quality, and operational management decisions, implies that LCA-based predictions of operational environmental impacts are systematically uncertain. While probabilistic LCA approaches can quantify this uncertainty, they cannot reduce it without empirical post-occupancy evaluation (POE) data that is rarely systematically collected and almost never fed back into LCA databases. Sharif and Hammad (2023) represent a notable exception, but their IoT-enabled operational LCA approach remains a prototype rather than a scalable industry standard.

7. Future Outlook and Research Roadmap

The trajectory of building LCA research over the 2020–2025 period points towards a convergence of four transformative forces that will define the next decade of the field: (1) mandatory whole-life carbon disclosure in building regulation; (2) the maturation of AI-driven LCA automation; (3) the operationalisation of circular economy principles in LCA methodology; and (4) the scaling of building LCA to urban and territorial levels. The future research roadmap depicted in Figure 4 organises priority research activities across short-term (2025–2027), medium-term (2027–2030), and long-term (2030–2035) horizons.

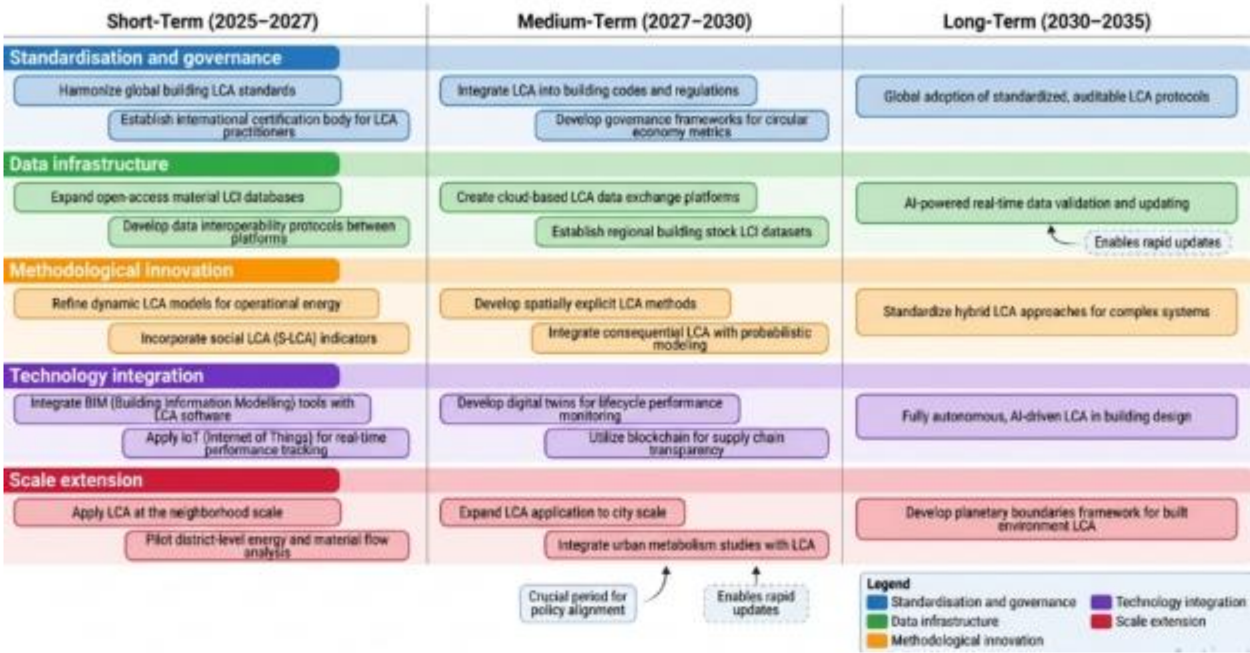

Figure 4. Future Research Roadmap for Building LCA: Short- (2025–2027), Medium- (2027–2030), and Long-Term (2030–2035) Research Priorities.

In the short term, the most impactful intervention available to the research community is the development of a globally harmonised WBLCA boundary protocol under ISO/CEN auspices. As documented by Passer et al. (2024) in the context of EU Level(s) framework implementation, the convergence of national LCA mandates towards a common methodological baseline is both technically feasible and politically proximate, given the alignment of interest among major construction markets in Europe, North America, and East Asia. Parallel short-term priorities include the expansion of climate-specific EPD databases for tropical, arid, and sub-Arctic contexts, building on existing initiatives such as the Australian AIRAH climate zone EPD project and nascent programmes in Southeast Asia and Sub-Saharan Africa.

In the medium term, the maturation of BIM-LCA interoperability through open IFC-to-LCA schema extensions represents the most consequential technological opportunity. Lützkendorf and Balouktsi (2022) argued compellingly that the integration of LCA outputs into building permit systems and energy performance certificates (EPCs), contingent on seamless BIM-to-LCA data flows — could catalyse industry-wide embodied carbon reduction at a scale unachievable through voluntary programmes alone. Medium-term research must also address the interpretability and transferability barriers currently limiting ML-LCA adoption, through the development of explainable AI (XAI) architectures, open-source benchmark datasets, and cross-validation protocols against process-based LCA results.

In the long term, the extension of building LCA to urban metabolism models and city digital twins represents both the greatest methodological challenge and the greatest potential leverage point for systemic decarbonisation. Lotteau et al. (2020) and Trigaux et al. (2021) have demonstrated the technical feasibility of neighbourhood-scale LCA, but scaling these approaches to cities of millions of buildings requires data integration architectures, governance frameworks, and computational infrastructures that do not currently exist. The integration of social LCA (S-LCA) and life cycle cost (LCC) dimensions into holistic building sustainability frameworks, addressing equity, health, and economic resilience alongside environmental performance, will be essential to ensure that the net-zero transition is not pursued at the expense of social sustainability.

Throughout all these horizons, the need for greater empirical grounding of LCA assumptions through post-occupancy evaluation, demolition material flow monitoring, and longitudinal building stock tracking remains paramount. The field's credibility as a decision-support tool for practitioners, policymakers, and investors ultimately depends on the demonstrated accuracy of its predictions, a standard that current LCA practice rarely subjects itself to with the rigour that its policy influence demands.

8. Conclusion

This systematic review has critically synthesised over four decades of cumulative methodological development compressed into five years of accelerating research output (2020–2025), revealing a field at an inflection point. Life cycle assessment has transitioned from a specialised research tool to a policy-relevant instrument for building decarbonisation, but its full potential is constrained by methodological fragmentation, data infrastructure deficits, and a persistent gap between methodological sophistication and practical implementation.

The central finding of this review is that the embodied carbon challenge, once peripheral to building environmental assessment, has become definitionally central to the net-zero buildings agenda, constituting the dominant lifecycle GHG burden for high-performance buildings and demanding urgent methodological, regulatory, and data infrastructure responses. The integration of BIM, machine learning, and dynamic LCA offers transformative possibilities for accelerating the feedback loop between design decisions and environmental performance evaluation, but realising these possibilities requires the kind of internationally coordinated standardisation effort that the field has historically struggled to achieve.

Climate zone sensitivity emerges from this review as a critically underexplored moderating variable with first-order consequences for LCA outcomes, material rankings, and policy recommendations. The dominance of European and North American research in the global building LCA literature creates a systematic bias that must be actively corrected through targeted investment in climate-specific data infrastructure and capacity building in the Global South.

The research agenda proposed in this review, centred on harmonised global protocols, open LCA data infrastructure, interpretable AI integration, circular economy methodologies, and urban-scale extension, represents a substantial but achievable programme of work. Progress on these priorities will determine whether building LCA fulfils its promise as the quantitative backbone of the global sustainable buildings transition or remains a methodologically complex tool that generates more uncertainty than insight. Given the scale of the decarbonisation challenge and the speed of the transformation required, the case for accelerated investment in this research agenda could not be more compelling.

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Author Contributions

The author has significantly contributed to the study's conception, design, data collection, analysis, and interpretation. All authors were involved in writing the manuscript or critically reviewing it for its intellectual value. They have reviewed and approved the final version for submission and publication and accept full responsibility for the content and integrity of the work.

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Conflicts of Interest

The authors state that there are no financial, personal, or professional conflicts of interest associated with this research.

Ethical Approvals

This research did not involve the use of human participants or animal subjects and therefore did not require ethical clearance

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