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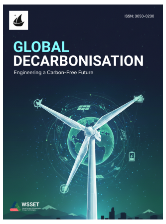

Review

Modular Construction and Climate Change Mitigation: Lifecycle Carbon Impacts of Prefabricated Housing Systems

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A B S T R A C T

The construction sector accounts for approximately 38% of global energy-related carbon dioxide (CO_2) emissions, yet evidence on whether modular and prefabricated housing genuinely reduces whole-life carbon remains fragmented and context-specific. This paper systematically synthesises 57 Scopus-indexed studies (2012–2026) on the lifecycle carbon performance of prefabricated residential buildings, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidance. Across the evidence base, prefabricated systems reduced construction-phase embodied carbon by 10–45% relative to conventional alternatives, with the largest savings associated with timber-based systems, high prefabrication rates, and short transport distances; module reuse at end-of-life recovered up to 30% of initial embodied carbon, and design for disassembly avoided up to 20% of demolition-phase emissions. Reported reductions, however, varied substantially with regional electricity mixes, system boundaries, and lifecycle assessment (LCA) assumptions. The paper's principal novelty is the Carbon–Context Alignment Framework (CCAF), an inductively derived conceptual model proposing that the climate efficacy of prefabrication is determined by the simultaneous alignment of four contextual dimensions: material carbon intensity, grid carbon factor, policy and regulatory environment, and social housing scale. An illustrative application demonstrates how the CCAF can be operationalised as a diagnostic tool for policymakers, developers, and designers seeking to configure prefabricated housing programmes for maximum climate mitigation benefit across low-, middle-, and high-income settings.

A R T I C L E I N F O

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LIST OF ABBREVIATIONS

Abbreviation	Definition
BIM	Building Information Modelling
CCAF	Carbon–Context Alignment Framework
CLT	Cross-Laminated Timber
CO_2	Carbon Dioxide
GHG	Greenhouse Gas
GWP	Global Warming Potential
IBS	Industrialised Building System

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Abbreviation	Definition
LCA	Lifecycle Assessment
LGSF	Light-Gauge Steel Frame
MiC	Modular Integrated Construction
MMC	Modern Methods of Construction
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses

1. INTRODUCTION

The construction sector is responsible for approximately 38% of global energy-related carbon dioxide (CO_2) emissions when operational and embodied carbon are considered together (Jin et al. 2020). The global housing stock is projected to grow by more than 230 billion square metres by 2060, driven primarily by rapid urbanisation in Asia, Africa, and Latin America (Tang et al. 2024). How residential buildings are designed and constructed over the coming decades will therefore have profound and lasting implications for climate trajectories. Against this backdrop, modular and prefabricated construction has attracted substantial academic and policy interest as an approach that could simultaneously address housing supply deficits and carbon reduction targets.

Modular construction is a building process in which structural components or whole volumetric units are manufactured off-site in controlled factory environments before being transported to site and assembled (Jin et al. 2020). The approach spans a wide spectrum of systems, including volumetric modular construction, panelised systems, hybrid methods, and industrialised building systems (IBS), each with distinct material profiles and lifecycle characteristics (Liu & Loo 2025). Related terms used throughout this paper include modern methods of construction (MMC), the umbrella policy term used in the United Kingdom; modular integrated construction (MiC), the volumetric approach mandated for many public projects in Hong Kong; cross-laminated timber (CLT), an engineered mass-timber panel product; and light-gauge steel frame (LGSF), a cold-formed steel system common in low- and mid-rise modular housing. Advocates argue that factory-controlled production reduces material waste, shortens construction timelines, improves quality control, and lowers construction-stage emissions through more efficient logistics (Tian & Spatari 2022). Many of these claimed advantages carry direct implications for a building's carbon footprint across its whole life.

Despite growing enthusiasm, the academic literature on the lifecycle carbon implications of prefabricated housing remains fragmented. Studies vary widely in their system boundaries, assessment methodologies, geographic contexts, and material assumptions, which makes comparative analysis difficult and confident generalisation premature. Some studies report substantial embodied carbon reductions in prefabricated systems, while others identify scenarios in which the manufacturing and transport demands of factory-produced components partially or wholly offset construction-stage gains (Greer & Horvath 2023). Operational carbon outcomes, which depend heavily on local energy grids and building envelope performance, further interact with embodied carbon in ways that shift over time and across geographies.

This paper responds to that complexity through a systematic synthesis of 57 studies retrieved from the Scopus database, using lifecycle assessment (LCA) evidence to map the conditions under which prefabrication delivers meaningful climate benefits.

1.1. NOVELTY AND CONTRIBUTION

This review differs from previous syntheses in three respects. First, whereas earlier reviews of off-site construction have concentrated on cataloguing environmental performance indicators (Jin et al. 2020) or on a single lens such as circular economy application (Liu & Loo 2025), this paper deliberately synthesises evidence across all lifecycle stages, embodied, operational, and end-of-life, for the residential sector specifically, where the housing-climate policy interface is most acute. Second, the paper moves beyond descriptive synthesis by explaining variation: it interrogates why reported carbon reductions range from marginal to 45%, tracing this heterogeneity to material selection, grid carbon intensity, transport distance, prefabrication rate, and system boundary definitions. Third, and most significantly, the paper advances a novel conceptual contribution, the Carbon–Context Alignment Framework (CCAF). The specific research gap that the CCAF addresses is the absence of a structured model linking construction-method carbon performance to the national and market context in which that method is deployed; existing sustainability assessment tools evaluate buildings, whereas the CCAF evaluates the alignment between a prefabrication strategy and its deployment context. For policymakers and practitioners, the framework functions as a diagnostic checklist for configuring modular housing programmes—identifying which contextual conditions (material supply chains, grid decarbonisation, regulation, and housing demand aggregation) are in place and which represent vulnerabilities, as demonstrated through an illustrative application in Section 4.5.

1.2. RESEARCH OBJECTIVES

This paper is guided by three interconnected research objectives:

1. To systematically map and characterise the current evidence base on the lifecycle carbon performance of prefabricated residential buildings;
2. To identify patterns, contradictions, and gaps in the literature with respect to embodied, operational, and whole-life carbon assessments; and
3. To synthesise the findings into a novel conceptual framework that advances understanding of contextually conditioned carbon outcomes in prefabricated housing.

2. METHODOLOGY

This study adopts a systematic literature review methodology conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidance. Each stage of the process, search design, screening, eligibility assessment, quality appraisal, and synthesis, is documented below to ensure transparency and reproducibility, and the selection process is summarised in the PRISMA flow diagram presented in Figure 1.

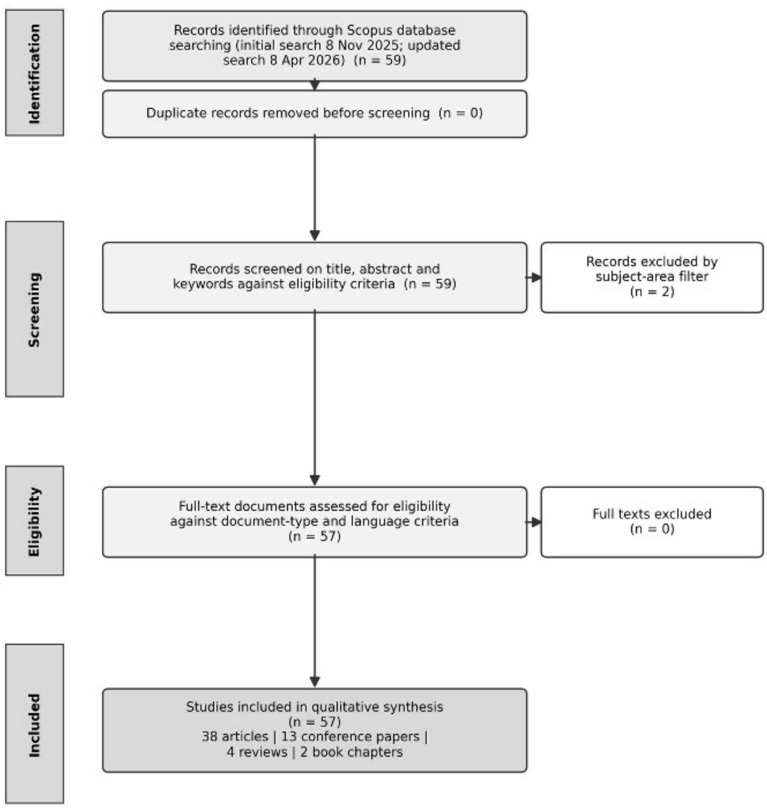

Figure 1. PRISMA 2020 flow diagram of the study identification, screening, eligibility, and inclusion process.

2.1. SEARCH STRATEGY AND STRING DEVELOPMENT

The research topic was deconstructed into four conceptual groups to enable a structured and comprehensive search, following a PICO-equivalent decomposition commonly used in systematic review methodology. Table 1 presents the four search groups and their associated keywords.

Table 1. Search group decomposition and associated keywords.

Group	Conceptual domain	Keywords / terms
1	Method (construction type)	"modular construction"; "offsite construction"; "off-site construction"; "prefabricated construction"; "prefabricated buildings"; "industrialized building system*"; "IBS"; "modular housing"; "prefab housing"
2	Goal (climate/carbon target)	"climate change mitigation"; "carbon reduction"; "carbon emission*"; "greenhouse gas emission*"; "GHG emission*"; "decarbonization"; "low carbon"; "net zero"
3	Assessment method (metrics)	"life cycle assessment"; "lifecycle assessment"; "LCA"; "life cycle analysis"; "lifecycle analysis"; "embodied carbon"; "operational carbon"; "whole life carbon"; "carbon footprint"
4	Research context (building type)	"residential building*"; "housing"; "dwelling*"; "housing system*"; "residential construction"

The four groups were combined with Boolean AND operators so that all four dimensions were present in every retrieved document, while OR operators within each group captured terminological variation across disciplines and regions. Wildcards (*) captured plural and variant forms. The final search string applied to titles, abstracts, and keywords (TITLE-ABS-KEY) was:
TITLE-ABS-KEY (("modular construction" OR "offsite construction" OR "off-site construction" OR "prefabricated construction" OR "prefabricated buildings" OR "industrialized building system*" OR "IBS" OR "modular housing" OR "prefab housing") AND ("climate change mitigation" OR "carbon reduction" OR "carbon emission*" OR "greenhouse gas emission*" OR "GHG emission*" OR "decarbonization" OR "low carbon" OR "net zero") AND ("life cycle assessment" OR "lifecycle assessment" OR "LCA" OR "life cycle analysis" OR "lifecycle analysis" OR "embodied carbon" OR "operational carbon" OR "whole life carbon" OR "carbon footprint") AND ("residential building*" OR housing OR dwelling* OR "housing system*" OR "residential construction")).

2.2. ELIGIBILITY CRITERIA

Beyond the language and subject-area filters applied within Scopus, explicit inclusion and exclusion criteria were defined a priori and applied at the screening and eligibility stages, as summarised below.

2.2.1. INCLUSION CRITERIA

1. Peer-reviewed journal articles, conference papers, review articles, or book chapters;
2. Published in English between 2012 and April 2026;
3. Addressing modular, prefabricated, off-site, or industrialised construction of residential or predominantly residential buildings; and
4. Reporting carbon, greenhouse gas (GHG), or lifecycle-based environmental performance evidence for at least one lifecycle stage.

2.2.2. EXCLUSION CRITERIA

1. Studies addressing exclusively non-residential typologies (e.g., offices, industrial facilities);
2. Studies concerned solely with structural, cost, or scheduling performance without any carbon or environmental dimension;
3. Editorials, news items, and non-scholarly material; and
4. Documents whose full text could not be retrieved.

2.3. SEARCH EXECUTION, SCREENING, AND STUDY SELECTION

The search string was executed in the Scopus database on 8 November 2025 and re-run on 8 April 2026 to capture newly indexed studies. The initial retrieval yielded 59 documents. Because a single database was searched, no cross-database duplicates arose; Scopus's automatic deduplication confirmed zero duplicate records. Title, abstract, and keyword screening, followed by full-text eligibility assessment, was performed independently by the two authors, with disagreements resolved through discussion until consensus was reached. The application of the subject-area filter (Engineering; Environmental Science; Energy; Computer Science; Earth and Planetary Sciences) excluded two records, while the document-type filter (article, conference paper, review, book chapter) and English-language filter excluded no further records. The final dataset therefore comprised 57 documents. Table 2 summarises the filtering sequence, and Figure 1 presents the corresponding PRISMA flow diagram.

Table 2. Search execution and filtering results.

Filter stage	Criteria applied	Documents retained
Initial search	Full Boolean string on TITLE-ABS-KEY in Scopus (8 Nov 2025; updated 8 Apr 2026)	59
Duplicate removal	Single-database search; no duplicates identified	59
Subject-area filter	Engineering; Environmental Science; Energy; Computer Science; Earth and Planetary Sciences	57
Document-type filter	Article; conference paper; review; book chapter	57
Language filter	English only	57
Final dataset	—	57

The 57 retained documents span publication years 2012 to 2026 and represent a geographically diverse set of research contexts, including the United Kingdom, mainland China, Hong Kong, Australia, South Korea, Malaysia, Portugal, Canada, and the United States. The dataset comprises 38 journal articles, 13 conference papers, 4 review articles, and 2 book chapters.

2.4. QUALITY APPRAISAL, DOCUMENT TYPES, AND RISK OF BIAS

Because the dataset spans four document types with differing levels of peer-review rigour, a structured quality appraisal was undertaken rather than treating all sources as equivalent. Each study was appraised against four criteria adapted from established LCA reporting practice:

1. clarity of goal and scope definition;
2. explicit statement of system boundary and functional unit;
3. transparency of data sources and emission factors; and
4. discussion of assumptions, limitations, or uncertainty.

Journal articles and review papers generally satisfied all four criteria. Conference papers and book chapters, which typically undergo lighter peer review, were retained only where they satisfied at least the first three criteria; their findings are used in this synthesis to corroborate patterns established by journal-published evidence rather than as sole support for any conclusion, and this weighting is made explicit where relevant in Sections 3 and 4.

Two potential sources of bias in the evidence base are acknowledged. First, publication bias may inflate the apparent benefits of prefabrication, since studies reporting positive carbon outcomes are more likely to be published than null or negative results. Second, the geographic concentration of studies in China, Hong Kong, and the United Kingdom, contexts with strong policy mandates for prefabrication, means the evidence base over-represents settings already favourable to modular construction. Both issues are considered further in the limitations (Section 4.9) and inform the cautious, context-conditional framing adopted throughout this paper.

2.5. ANALYTICAL APPROACH

A thematic content analysis was employed. Each study was assessed against a structured extraction framework encompassing:

1. geographic and climatic context;

2. construction system type;
3. lifecycle stage assessed;
4. comparative baseline;
5. key carbon metric reported; and
6. principal findings.

Extracted data were organised thematically to identify patterns, contradictions, and convergences. Where individual studies report specific carbon figures, those figures are quoted directly and contextualised within the wider synthesis. No attempt was made to statistically pool results into a single averaged estimate. This was a deliberate methodological choice: the included studies differ substantially in calculation methods, system boundaries, functional units, and assumptions about materials, transport, and building lifespan, and pooling across such heterogeneous conditions would risk producing a misleading average that represents no single context accurately. This approach is consistent with established practice in systematic reviews where study heterogeneity is high (Jin et al. 2020). The analysis instead prioritises understanding why findings differ across studies and what those differences reveal about the conditions under which prefabrication performs best from a carbon standpoint.

3. RESULTS

3.1. OVERVIEW OF THE EVIDENCE BASE

The 57 included studies reflect markedly growing interest in the intersection of prefabricated construction and lifecycle carbon assessment, with publication volume accelerating noticeably from 2019 onwards. Mainland China and Hong Kong account for a substantial share of the evidence base, reflecting both the scale of prefabrication adoption in those contexts and government-mandated carbon reduction policies in the construction sector. The United Kingdom emerges as the second most represented geography, consistent with national commitments under the Climate Change Act 2008 and the UK government's promotion of MMC as a response to both housing shortfall and decarbonisation imperatives (Narula & Finnegan 2025). Table 3 summarises, and Figure 2 visualises, the geographic distribution of included studies.

Table 3. Geographic distribution of included studies.

Geographic region	Studies (n)	Representative studies
China (Mainland)	14	Du et al. (2019); Han et al. (2022); Xu & Chang (2026); Dong et al. (2025)
Hong Kong	9	Teng & Pan (2019, 2020); Zhang et al. (2024, 2026); Wen et al. (2024); Wu et al. (2025)
United Kingdom	8	Narula & Finnegan (2025); Kechidi & Banks (2023); Arslan et al. (2023); Nangir et al. (2026)
North America / Australia	6	Greer & Horvath (2023); Klammer et al. (2022); Dara & Hachem-Vermette (2019)
Europe (excl. UK)	5	Rossi et al. (2012); Tavares et al. (2019); Lukić et al. (2020); Jeleniewicz et al. (2025)
Southeast / South Asia	4	Manap et al. (2025); Jia Wen et al. (2015); Bukoski et al. (2017)
Multi-country / Global	11	Jin et al. (2020); Liu & Loo (2025); Luo & Chen (2020)

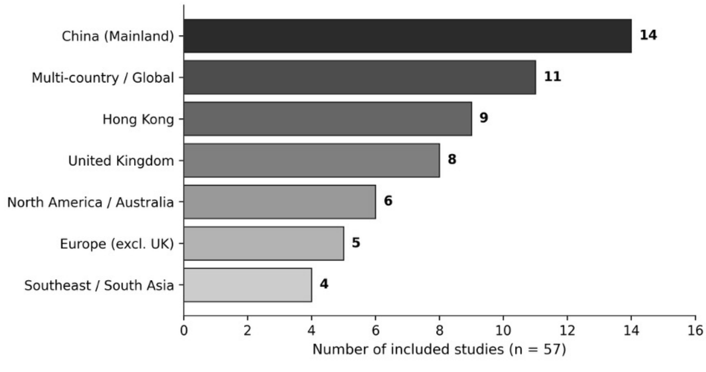

Figure 2. Geographic distribution of the 57 included studies.

3.2. LIFECYCLE PHASES AND CARBON ASSESSMENT SCOPE

A notable finding concerns the unequal distribution of research attention across lifecycle stages. Figure 3 illustrates the lifecycle stages of a residential building, expressed using the EN 15978 modular structure, together with the five system boundaries adopted across the review dataset; Table 4 provides the corresponding breakdown. The majority of studies focus primarily or exclusively on the construction phase, particularly the embodied carbon of material manufacturing and factory or on-site assembly. Fewer studies integrate operational carbon in a whole-life perspective, and end-of-life assessment remains substantially under-represented.

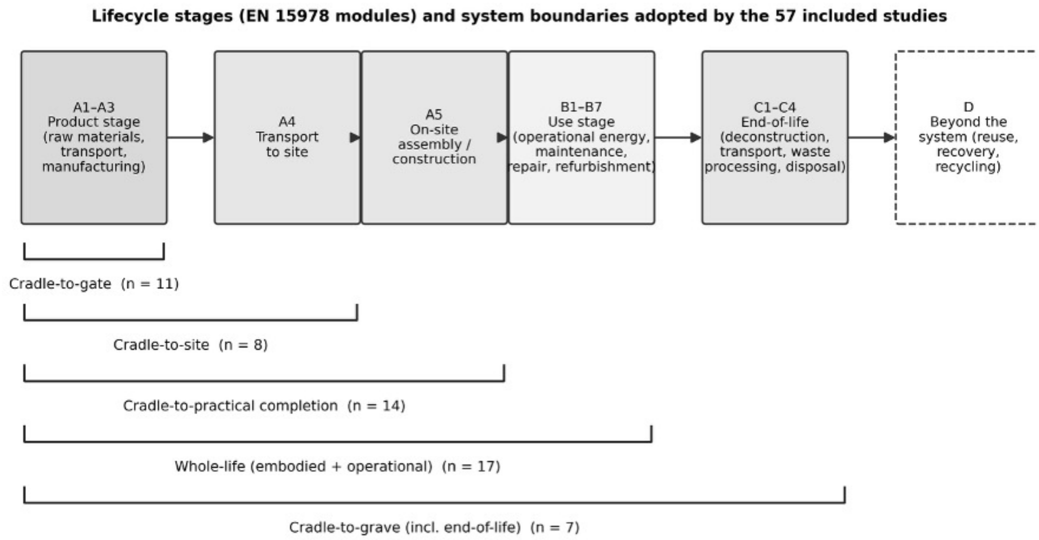

Figure 3. Lifecycle stages (EN 15978 modules) and the system boundaries adopted by the included studies.

Table 4. Distribution of lifecycle scope across included studies.

Lifecycle scope	Description	Studies (approx. n)	Example references
Cradle-to-gate	Manufacturing only; no transport or operational phase	11	Xu et al. (2021); Jin et al. (2025)
Cradle-to-site	Manufacturing + transport to site	8	Du et al. (2019); Xu & Chang (2026)
Cradle-to-practical completion	Manufacturing + transport + on-site assembly	14	Teng & Pan (2019); Zhang et al. (2024)
Whole-life (embodied + operational)	Embodied + operational carbon over building lifespan	17	Narula & Finnegan (2025); Nangir et al. (2026)
Cradle-to-grave (incl. end-of-life)	Full lifecycle including demolition, reuse, and recycling	7	Wen et al. (2024); Liu & Loo (2025)

Wen et al. (2024) conducted one of the most comprehensive end-of-life assessments in the dataset, finding that steel-framed modular buildings in Hong Kong hold significant carbon savings potential at disassembly, particularly where modules can be reused rather than recycled or landfilled; reuse scenarios recovered up to 30% of the initial embodied carbon investment. Liu and Loo (2025) similarly evaluated MiC lifecycle assessments within a circular economy framework and found that design-for-disassembly principles substantially improve whole-life carbon performance.

3.3. EMBODIED CARBON PERFORMANCE: KEY QUANTITATIVE EVIDENCE

The literature reveals a broadly consistent, though not universal, pattern: prefabricated and modular systems tend to produce lower embodied carbon during the construction phase than conventional cast-in-situ or masonry alternatives. The magnitude of the reduction, however, varies substantially, from marginal improvements to savings approaching 45%, depending on material system, geographic context, prefabrication rate, and system boundary. Table 5 summarises the quantitative reductions reported across key studies.

Table 5. Reported embodied carbon reductions in selected studies

Study	Country / region	System type	Comparison baseline	Reduction reported
Tian & Spatari (2022)	China	Prefabricated concrete	Cast-in-situ concrete	10–20%
Teng & Pan (2019)	Hong Kong	Prefabricated high-rise	Conventional concrete	15–25%
Greer & Horvath (2023)	California, USA	Modular construction	Conventional site-built	Up to 45%
Jang et al. (2022)	South Korea	Modular residential	Conventional concrete	~22%
Kechidi & Banks (2023)	UK	Steel-framed modular	Traditional masonry	~18%
Du et al. (2019)	China	Prefabricated residential	Traditional construction	5–35% (variable)
Nangir et al. (2026)	UK	LGSF modular	Conventional masonry	20–30%
Tavares et al. (2019)	Portugal	Modular 'Moby' house	Benchmark residential	Significant reduction
Wu et al. (2025)	Hong Kong	Volumetric modular vs. panelised	Conventional concrete	7–18%

Tian and Spatari (2022) found that prefabricated concrete structures in China produced 10–20% lower construction-phase emissions than cast-in-situ equivalents, though the advantage narrowed as transport distances extended. Du et al. (2019) corroborated this directional finding in a cradle-to-site analysis, noting that prefabrication rates above 50% were associated with lower CO_2 emissions, but that the relationship was non-linear and subject to diminishing returns above certain thresholds.

For timber-based systems, the evidence is particularly encouraging. Younis and Dodoo (2022) compared CLT, light-frame timber, and reinforced concrete residential buildings and found that CLT achieved substantially lower global warming potential (GWP) across the construction phase, with carbon storage in timber products providing an additional climate benefit not captured within many conventional LCA boundaries. Jeleniewicz et al. (2025) confirmed this in a European context, concluding that modular timber structures outperformed equivalent steel-framed alternatives on both embodied carbon and circularity metrics.

Greer and Horvath (2023) produced one of the more ambitious claims in the dataset, suggesting that modular construction in California's housing sector could reduce embodied carbon by up to 45% relative to site-built equivalents, a figure the authors themselves acknowledge depends heavily on assumptions about factory energy source, transport distance, and structural material. This highlights a recurring methodological challenge: extreme efficiency gains in controlled studies often rest on optimistic assumptions that may not translate uniformly to practice.

3.4. OPERATIONAL CARBON AND ENERGY GRID DEPENDENCY

While embodied carbon has attracted the most consistent research attention, operational carbon, arising from the energy used to heat, cool, ventilate, and power residential buildings, remains the dominant carbon source over a 50–80 year lifespan in many contexts. The relationship between construction method and operational performance is, however, less direct than embodied carbon comparisons might suggest, because operational outcomes are mediated by factors largely independent of the construction method itself: occupant behaviour and household energy practices; the efficiency of heating, ventilation, and air-conditioning (HVAC) systems installed and their replacement cycles; prevailing climatic conditions and their evolution over the building's life; and the building's retrofit potential, since envelope and services upgrades over a multi-decade lifespan can reshape the operational carbon profile substantially.

Narula and Finnegan (2025) examined LGSF modular housing in the context of the UK social housing crisis, finding that operational carbon outcomes depended critically on insulation specification and on the carbon intensity of the national electricity grid. Their modelling demonstrated that under current UK grid conditions, LGSF housing could achieve net zero operational targets with appropriate thermal envelopes, but that this advantage would narrow in contexts with carbon-intensive generation. Tumminia et al. (2018) reinforced this through their assessment of a prefabricated net zero energy building module in Italy: high-performance envelopes combined with on-site renewable generation rendered the operational footprint negligible, but only where solar irradiation and grid decarbonisation aligned favourably.

Nangir et al. (2026) went further in their UK social housing analysis, evaluating whole-life carbon performance of LGSF modular construction incorporating bio-based insulation and geopolymer concrete alternatives. Material innovation within modular systems, particularly substituting high-embodied-carbon materials such as Portland cement concrete with lower-impact alternatives, offered compounding benefits across both embodied and operational carbon categories. Nonetheless, the operational evidence base remains thinner than modelling studies imply: few included studies incorporate measured post-occupancy data, meaning that performance gaps between designed and actual energy use, driven largely by occupant behaviour and HVAC operation, are rarely captured.

3.5. END-OF-LIFE CARBON AND THE CIRCULAR ECONOMY OPPORTUNITY

End-of-life carbon is the most consistently neglected lifecycle stage in the prefabricated housing literature, yet it represents both a significant risk and a substantial opportunity. Prefabricated systems, by virtue of their modular and often demountable architecture, are theoretically well positioned to support circular economy strategies including disassembly, module reuse, and material recovery.

Wen et al. (2024) produced the most detailed end-of-life carbon analysis in this review, demonstrating through a case study of steel-framed modular buildings in Hong Kong that end-of-life carbon savings can be considerable where modules are reused rather than demolished, with reuse significantly outperforming recycling. Liu and Loo (2025) similarly found that circular economy thinking applied to MiC in Hong Kong improved whole-life carbon performance, though they cautioned that circular outcomes depend on reverse logistics infrastructure that remains immature in most markets. Rajanayagam et al. (2024) examined flat-pack modular systems and identified design for disassembly as a critical variable, finding that systems specifically designed for disassembly could avoid up to 20% of the demolition-phase emissions typical of conventional buildings.

These theoretical benefits, however, face substantial practical barriers that the literature is only beginning to address. Module reuse in practice is constrained by the absence of established secondary markets for used modules; regulatory challenges, including building code recertification of reused structural elements, warranty and liability uncertainty, and the lack of standardised material documentation or 'module passport' systems; logistical challenges of storing, transporting, and refurbishing large volumetric units between uses; and unresolved questions of economic feasibility, since disassembly is more labour-intensive than demolition and its business case depends on residual module value that current markets do not reliably price. Material degradation over a first service life, including connection fatigue in steel systems, moisture-related deterioration in timber, and sealant and gasket ageing, further limits which modules will realistically be fit for reuse. Until these barriers are addressed through policy and industry standardisation, the end-of-life carbon savings modelled in the literature should be read as an upper bound on achievable performance rather than an expected outcome.

4. DISCUSSION

4.1. PATTERNS AND CONTRADICTIONS IN THE LITERATURE

The 57 reviewed studies reveal a broad directional consensus: prefabricated and modular construction tends to reduce construction-phase embodied carbon relative to conventional methods. The literature is nonetheless marked by significant heterogeneity in findings, methodologies, and contextual assumptions that cautions against uncritical generalisation. Three dominant sources of variation deserve particular attention: material selection, system boundary definition, and geographic or climatic context. Each is examined below, followed in Section 4.2 by a closer interrogation of why reported carbon reductions vary so widely.

The first source of variation is material selection. Steel-framed modular systems produce markedly different carbon profiles from timber or concrete alternatives. Kechidi and Banks (2023) found that steel-framed modular housing in the UK generated meaningful upfront carbon savings relative to masonry construction, but noted that the high embodied carbon of structural steel makes whole-life comparisons sensitive to assumptions about end-of-life recycling rates and grid decarbonisation trajectories. Timber systems, by contrast, benefit from biogenic carbon sequestration, negative or near-zero embodied carbon for structural elements under some accounting frameworks, and strong alignment with circular economy principles (Lukić et al. 2020; Jeleniewicz et al. 2025). This advantage must, however, be weighed against countervailing considerations that the timber-focused literature often understates. Fire safety requirements for mass-timber and light-frame systems, particularly in mid- and high-rise applications, can necessitate additional encapsulation materials and design compensations that erode part of the embodied carbon advantage. Moisture durability is a genuine risk for timber modules exposed during transport, storage, and assembly, with implications for both service life and warranty. Engineered timber supply chains remain geographically concentrated, and regional availability constraints, acute in most of Africa, the Middle East, and parts of Asia, mean that imported CLT can carry significant transport emissions and cost premiums that alter the carbon and economic calculus. A balanced reading of the evidence therefore positions timber as highly promising where regulatory, climatic, and supply chain conditions permit, rather than as a universal solution.

The second source of variation is system boundary definition. Studies adopting cradle-to-gate or cradle-to-site boundaries naturally report lower overall carbon figures than those employing whole-life or cradle-to-grave frameworks, making direct comparison hazardous without careful boundary harmonisation, a methodological challenge that Jin et al. (2020) identified as among the most significant barriers to confident knowledge synthesis in this field. Building Information Modelling (BIM)-integrated LCA approaches, explored by Hao et al. (2020) and Xu et al. (2021), offer promising pathways towards more consistent and granular carbon accounting, but their adoption remains uneven across geographies and industry sectors.

The third source of variation is geographic and climatic context. Studies from temperate European climates produce different operational carbon trajectories from tropical or cold-climate studies, given differential heating and cooling demands. Bukoski et al. (2017) demonstrated this in their assessment of an energy-positive modular residence in Thailand, where high solar irradiation enabled near-zero operational carbon despite relatively modest envelope performance. Shahi et al. (2020) similarly showed that modular approaches to residential tower adaptation in cold Canadian climates produced different cost–carbon trade-offs from equivalent projects in milder climates.

4.2. EXPLAINING VARIATION IN REPORTED CARBON REDUCTIONS

Why do reported embodied carbon reductions range from 5% to 45% across studies of nominally similar interventions? Four interacting mechanisms emerge from the synthesis.

Regional electricity mix. Factory-based production shifts energy demand from diesel-powered site plant to grid electricity. Where the grid is coal-dominant, this shift can erode or reverse the expected benefit; where it is renewable-dominant, factory production compounds the advantage. This mechanism explains much of the gap between, for example, optimistic Californian results (Greer & Horvath 2023) and more modest findings from coal-intensive grids. It also implies that the carbon case for prefabrication will strengthen mechanically as national grids decarbonise, since factory electricity demand is progressively cleaned at no additional cost to the builder.

Transport distance. Module transport is carbon-intensive per tonne-kilometre relative to bulk material delivery, because volumetric modules ship significant empty space. Tian and Spatari (2022) showed the prefabrication advantage narrowing as factory-to-site distances extended; beyond context-specific thresholds, transport emissions can offset factory-stage savings entirely. Reported reductions therefore depend on the (often unstated) assumed distance between factory and site.

Prefabrication rate. Du et al. (2019) demonstrated that carbon savings scale non-linearly with the proportion of the building manufactured off-site: gains accrue steeply up to roughly 50% prefabrication and then flatten, exhibiting diminishing returns. Studies comparing high-prefabrication-rate systems with conventional baselines will consequently report larger reductions than studies of hybrid systems, even within the same market.

System boundary and LCA assumptions. Finally, part of the reported variation is an artefact of measurement rather than of performance. Narrow cradle-to-gate boundaries concentrate attention on the stages where prefabrication performs best, inflating apparent reductions; whole-life boundaries dilute the same absolute saving across a much larger denominator. Choices of functional unit (per square metre versus per dwelling), building lifespan, and end-of-life allocation rules further shift results in ways that are rarely harmonised across studies. Sensitivity analyses, where reported (e.g., Teng & Pan, 2020), confirm that boundary and assumption choices can alter reduction estimates by margins comparable to the differences between construction methods themselves.

4.3. UNCERTAINTY IN LIFECYCLE ASSESSMENT EVIDENCE

Closely related to the above, the review's quantitative findings must be read against the substantial uncertainty embedded in LCA methodology itself. Four sources of uncertainty warrant explicit acknowledgement. First, emission factor uncertainty: embodied carbon estimates depend on background databases whose factors for the same material can differ considerably across databases, regions, and vintages, propagating directly into reported reductions. Second, functional unit variability: studies normalise results per square metre of gross floor area, per dwelling, or per building, and these choices are not interconvertible without information that is often unreported, limiting cross-study comparability. Third, building lifespan assumptions: whole-life results are highly sensitive to the assumed service life (commonly anywhere between 50 and 80 years in the included studies); longer assumed lifespans amortise embodied carbon over more years of operation and shift the embodied–operational balance accordingly. Fourth, future grid decarbonisation scenarios: whole-life studies must assume a trajectory for grid carbon intensity decades into the future, and static-grid assumptions systematically overstate operational carbon relative to scenarios reflecting legislated decarbonisation commitments. Teng and Pan (2020) demonstrated formally that parameter, scenario, and model uncertainties of these kinds can materially change embodied carbon estimates for prefabricated high-rise buildings. The quantitative ranges reported in this review should therefore be interpreted as indicative envelopes rather than precise expectations, and future primary studies should routinely report sensitivity analyses across these four dimensions.

4.4. POSITIONING AGAINST PREVIOUS REVIEWS

The findings of this synthesis both confirm and extend earlier review work. Jin et al. (2020), in their critical review of the environmental performance of off-site constructed facilities, concluded that off-site methods generally outperform conventional construction on waste and emissions but that methodological inconsistency prevents firm quantification; the present review confirms both conclusions on a more recent and residential-specific evidence base, and adds quantitative structure by mapping the reported reduction ranges (10–45%) to their explanatory conditions (Section 4.2). Liu and Loo (2025), reviewing MiC lifecycle assessments through a circular economy lens, emphasised end-of-life potential and reverse logistics immaturity; this review corroborates their conclusions while situating end-of-life within a whole-life and multi-context framing. Two points of tension with earlier syntheses deserve note. First, whereas some earlier review work implicitly treats the carbon benefit of prefabrication as a property of the method, the evidence assembled here indicates the benefit is conditional on context—the central claim formalised in the CCAF. Second, this review is more cautious about headline reduction figures than some prior syntheses, given the boundary and uncertainty artefacts documented in Sections 4.2 and 4.3. The added contribution of this synthesis is therefore threefold: a residential-sector focus across all lifecycle stages, an explanatory (rather than solely descriptive) treatment of heterogeneity, and a transferable conceptual framework linking method to context.

4.5. THE CARBON–CONTEXT ALIGNMENT FRAMEWORK (CCAF)

The central theoretical contribution of this paper is the Carbon–Context Alignment Framework (CCAF), developed inductively through the systematic synthesis of the 57 included studies. The CCAF proposes that the climate efficacy of prefabricated housing cannot be determined by construction method alone, but is the product of four simultaneously operating contextual dimensions:

1. Material Carbon Intensity;
2. Grid Carbon Factor;
3. Policy and Regulatory Environment; and
4. Social Housing Scale.

Figure 4 presents the framework schematically, and Table 6 defines each dimension with its supporting evidence.

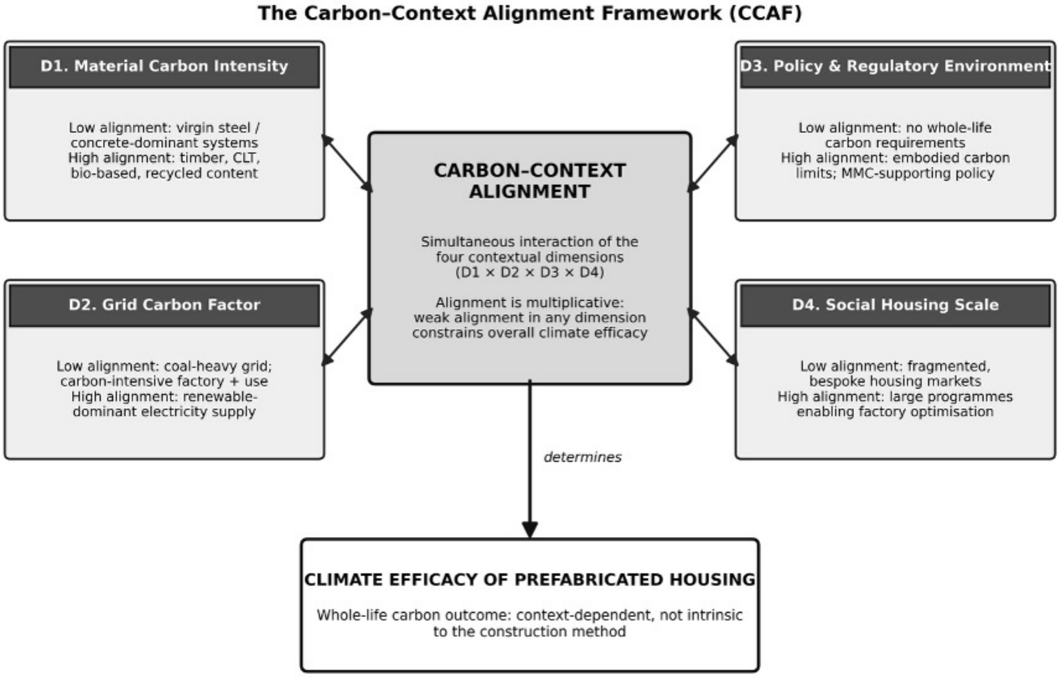

Figure 4. The Carbon–Context Alignment Framework (CCAF): four contextual dimensions interact multiplicatively to determine the climate efficacy of prefabricated housing.

Table 6. CCAF dimensions, definitions, and supporting evidence.

CCAF dimension	Definition	Low alignment	High alignment	Key evidence
1. Material Carbon Intensity	Embodied carbon of structural and envelope materials	Virgin steel / concrete-dominant systems	Timber, CLT, bio-based, or recycled-content systems	Jeleniewicz et al. (2025); Younis & Dodoo (2022); Nangir et al. (2026)
2. Grid Carbon Factor	Carbon intensity of the electricity grid serving factory production and building operation	Coal-heavy grid	Renewable-dominant grid	Narula & Finnegan (2025); Tumminia et al. (2018); Bukoski et al. (2017)
3. Policy & Regulatory Environment	Mandates, incentives, and standards shaping prefabrication adoption and carbon compliance	No whole-life carbon requirements; IBS not incentivised	Mandatory embodied carbon limits; MMC-supporting policy; net zero building codes	Manap et al. (2025); Jia Wen et al. (2015); Garrison et al. (2025)
4. Social Housing Scale	Volume and aggregation of housing demand enabling industrialised production at scale	Fragmented, bespoke housing markets	Large-scale programmes enabling factory optimisation and supply chain maturity	Narula & Finnegan (2025); Iuorio et al. (2019); Renger et al. (2018)

The CCAF proposes that maximum climate benefit from prefabrication is achievable only when all four dimensions are favourably aligned, and that alignment is effectively multiplicative rather than additive: weak alignment in any single dimension constrains the benefit obtainable from strength in the others. A country with a decarbonised grid but no whole-life carbon policy will not realise prefabrication's full potential; a nation with progressive regulation but a sector dominated by energy-intensive steel modules produced in coal-powered factories will find prefabrication delivering disappointing results in practice.

4.5.1. OPERATIONALISATION AND WEIGHTING

Although the CCAF is presented here as a conceptual framework, it is designed to be quantitatively implementable. Each dimension can be scored on a normalised 0–1 scale using observable indicators: Material

Carbon Intensity via the embodied carbon coefficient ($kgCO_2e/m^2$) of the dominant structural system relative to regional benchmarks; Grid Carbon Factor via published national grid intensity (gCO_2/kWh) normalised against global best and worst performers; Policy and Regulatory Environment via a checklist index of instruments in force (embodied carbon limits, whole-life carbon disclosure, MMC procurement mandates, net zero building codes); and Social Housing Scale via the annual volume of aggregated public or programmatic housing procurement relative to factory minimum-efficient-scale thresholds. An overall alignment index can then be computed as the geometric mean of the four scores, a formulation that operationalises the framework's multiplicative logic by penalising imbalance across dimensions. Differential weighting of dimensions is possible and may be justified where evidence indicates one dimension dominates in a given context, or instance, weighting the Grid Carbon Factor more heavily in hot climates with high cooling loads, but the default equal-weight geometric formulation is recommended until empirical calibration studies accumulate. Validating and calibrating this index against measured project outcomes is identified as a priority for future research.

4.5.2. ILLUSTRATIVE APPLICATION

The framework's diagnostic use can be illustrated by contrasting two deployment contexts drawn from the evidence base. In the United Kingdom, a proposed LGSF modular social housing programme would score highly on Grid Carbon Factor (a rapidly decarbonising grid), Policy and Regulatory Environment (MMC-supporting policy and forthcoming whole-life carbon requirements), and Social Housing Scale (aggregated public procurement), but only moderately on Material Carbon Intensity (steel-dominant systems); the CCAF correctly predicts the pattern observed by Narula and Finnegan (2025) and Nangir et al. (2026), strong but improvable performance, with material substitution (bio-based insulation, geopolymer concrete) the highest-leverage intervention. In Malaysia, by contrast, an IBS high-rise programme would score highly on Social Housing Scale and moderately on Policy (IBS-score mandates) but lower on Grid Carbon Factor, consistent with the more modest reductions reported by Manap et al. (2025); here the framework indicates that grid decarbonisation and factory energy sourcing, rather than further prefabrication mandates, constitute the binding constraint. Applied prospectively, for example, to emerging modular initiatives in sub-Saharan African cities—the CCAF functions as a structured checklist identifying which contextual preconditions are in place and which require sequenced investment before prefabrication can deliver its promised climate benefits.

4.5.3. DISTINCTION FROM EXISTING ASSESSMENT FRAMEWORKS

The CCAF differs in kind from established sustainability assessment frameworks in construction. Building rating systems such as BREEAM, LEED, and Green Star evaluate the performance of an individual building or asset against multi-criteria environmental checklists; LCA standards such as EN 15978 and ISO 14040/14044 prescribe how to measure lifecycle impacts of a defined product system. Neither class of instrument addresses the question the CCAF targets: whether a construction method, deployed in a particular national and market context, will deliver climate benefits. The CCAF is thus a context-alignment diagnostic operating at the level of programmes and policy environments rather than individual buildings, and is intended to complement—not substitute for—building-level rating and LCA tools.

4.6. SCALABILITY IN RAPIDLY URBANISING DEVELOPING ECONOMIES

The CCAF's Social Housing Scale dimension raises a question of particular consequence for developing economies, where the majority of projected housing growth to 2060 will occur (Tang et al. 2024): can modular construction scale under rapidly urbanising, resource-constrained conditions? Four constraints emerge as critical. First, supply chain readiness: prefabrication presupposes reliable upstream supply of processed materials, components, and logistics services that remain underdeveloped in many low-income countries, where cement, steel, and engineered timber are frequently imported at volatile prices. Second, manufacturing infrastructure: volumetric modular production requires significant capital investment in factories, moulds, and handling equipment, together with dependable electricity supply, itself scarce in many rapidly urbanising regions, creating a chicken-and-egg problem in which factories await demand certainty while programmes await factory capacity. Third, workforce transition: industrialised construction shifts labour demand from abundant low-skilled site labour towards factory technicians, logistics operators, and precision assemblers, requiring training systems that take years to establish and raising distributional questions in labour markets where construction is a major employer of low-income workers. Fourth, affordability: the cost premium of early-stage industrialised construction, before economies of scale are achieved, can conflict directly with the affordability imperative of social housing programmes. These constraints do not negate the CCAF's logic; rather, they specify its sequencing implication, that in low-income, high-growth contexts, investments in grid capacity, material supply chains, workforce development, and demand aggregation are preconditions for, not consequences of, climate-effective modular housing at scale.

4.7. REBOUND EFFECTS AND INDIRECT TRADE-OFFS

A further consideration, largely absent from the included studies, is the possibility of rebound effects accompanying large-scale prefabrication adoption. Modular construction's principal industrial attractions—speed, cost predictability, and a perception of environmental superiority, could plausibly stimulate higher overall construction volumes than would otherwise occur, partially or wholly offsetting per-unit carbon savings through aggregate material consumption. Analogous mechanisms are well documented in energy economics, where efficiency improvements induce additional demand. In housing, faster delivery may also encourage larger dwelling sizes, shorter redevelopment cycles, or speculative overbuilding, each carrying embodied carbon consequences. None of the 57 included studies quantifies such effects, which represents a substantive gap: lifecycle assessments compare buildings one-for-one and are structurally blind to volume effects at market scale. Future research combining LCA with construction-market modelling is needed to establish whether, and under what policy conditions (for example, whole-life carbon budgets applied at portfolio or municipal scale), prefabrication's per-unit savings survive aggregation. Acknowledging this possibility does not weaken the case for modular construction, but it does argue for embedding prefabrication within absolute carbon governance frameworks rather than treating per-unit efficiency as sufficient.

4.8. IMPLICATIONS FOR POLICY AND PRACTICE

Read through the lens of the CCAF, the synthesised evidence yields three implications for policy and professional practice. First, whole-life carbon accounting must become standard in building regulation and procurement. The current dominance of cradle-to-gate and cradle-to-site LCA systematically undervalues operational carbon and fails to incentivise end-of-life planning. Mandatory whole-life carbon assessment, as being progressively introduced in England through forthcoming Future Homes Standard regulations, is a step in the right direction; comparable mandates are urgently needed in the rapidly urbanising markets of the Global South.

Second, material innovation within prefabricated systems deserves greater policy and investment attention. Several included studies demonstrate that substituting conventional structural materials with lower-carbon alternatives, engineered timber, bio-based insulation, geopolymer concrete, can dramatically improve the carbon performance of otherwise conventionally configured modular systems (Nangir et al. 2026; Lukić et al. 2020). Procurement frameworks that incentivise or require such substitution within modular supply chains could unlock substantial carbon co-benefits.

Third, circular economy thinking must be embedded in modular housing design from the earliest project stages. The evidence from Wen et al. (2024), Liu and Loo (2025), and Rajanayagam et al. (2024) consistently identifies end-of-life module reuse as the highest-value carbon recovery strategy in prefabricated construction, yet reuse requires design decisions, connection detailing, material documentation, and reverse logistics infrastructure to be in place long before a building reaches end of life. Policy mechanisms that reward design for disassembly and establish module passport systems, analogous to product passports under the EU Circular Economy Action Plan, could catalyse a significant shift in practice.

4.9. LIMITATIONS OF THE REVIEW AND EVIDENCE BASE

Several limitations should be acknowledged. First, the review relied on a single database (Scopus) and was restricted to English-language publications, which may have excluded relevant research published in Chinese, Korean, Portuguese, or other languages and in sources indexed elsewhere; this plausibly contributes to the geographic imbalance of the evidence base, which over-represents China, Hong Kong, and the United Kingdom while under-representing Africa, Latin America, and much of South Asia, precisely the regions where future housing growth is concentrated. Second, the heterogeneity of LCA methodologies, system boundaries, and functional units across included studies prevented quantitative meta-analysis; the synthesis is therefore narrative and thematic, and the reported reduction ranges should not be read as pooled estimates. Third, the inclusion of conference papers and book chapters, while broadening coverage, introduces variability in peer-review rigour that the quality appraisal in Section 2.4 mitigates but cannot eliminate. Fourth, publication bias towards positive findings may inflate the apparent benefits of prefabrication. Finally, studies indexed after the updated search date of 8 April 2026 are not captured. Future research employing harmonised LCA protocols, as recommended by Jin et al. (2020), together with multi-database and multi-language searching, would substantially strengthen the evidence base.

5. CONCLUSION

This paper has systematically synthesised 57 studies on the lifecycle carbon implications of prefabricated residential housing. Quantitatively, the evidence indicates that prefabricated systems reduce construction-phase embodied carbon by 10–45% relative to conventional alternatives, with reductions scaling non-linearly with prefabrication rate and narrowing with transport distance; that timber-based systems consistently outperform steel and concrete alternatives on embodied carbon where supply chains and regulation permit; that operational carbon outcomes are governed less by construction method than by envelope specification and grid carbon intensity; and that end-of-life module reuse can recover up to 30% of initial embodied carbon, with design for disassembly avoiding up to 20% of demolition-phase emissions—albeit these end-of-life figures currently represent upper bounds pending resolution of regulatory, logistical, and market barriers.

The paper's principal scientific contribution is the Carbon–Context Alignment Framework. The CCAF reframes the research question from whether modular construction reduces carbon to under what alignment of material, grid, policy, and market conditions it does so, formalising the context-dependence that this synthesis documents empirically. In doing so it supplies what descriptive syntheses and building-level assessment tools do not: a transferable, operationalisable diagnostic for evaluating prefabrication strategies at programme and policy scale, applicable across settings as diverse as the housing estates of northern England, the high-rise towers of Hong Kong, and the emerging urban centres of sub-Saharan Africa.

Three directions for future research follow. First, empirical calibration and validation of the CCAF alignment index against measured project outcomes across contrasting national contexts. Second, harmonised, multi-database primary research addressing the field's structural gaps: measured post-occupancy operational data, end-of-life performance under real market conditions, and evidence from the under-represented regions of Africa, Latin America, and South Asia. Third, integration of lifecycle assessment with construction-market modelling to quantify potential rebound effects and to test whether per-unit carbon savings survive aggregation at market scale. Pursued together, these agendas would convert the conditional promise documented in this review into a reliable instrument of climate mitigation policy.

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AUTHOR CONTRIBUTIONS

Benjamin Moral: Conceptualisation: developed the themes and objectives of the review. Methodology: designed the review framework and criteria for literature selection. Literature review: conducted the comprehensive search and analysis of relevant literature. Writing – original draft: wrote the initial manuscript. Writing – review and editing: contributed to revision for clarity and coherence. **William Idakwoji**: Data curation: organised and synthesised data from selected studies. Writing – review and editing: assisted in editing and refining the final manuscript, ensuring accuracy and completeness. Supervision: supervised the study. All authors have read and approved the final version of the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

DATA ACCESSIBILITY

Data are available upon reasonable request made through the corresponding author.

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