A Life Cycle Framework Model for Quantifying the Carbon Footprint of Green Buildings Based on the Indonesian Building Code, Case Study: Engineering Tower, Sriwijaya University, Palembang

Mochammad Sulton Sahara[1], *Anis Saggaff[2], Mahmood Md. Tahir[3], Kiagus Muhammad Aminuddin[4]
[1] Civil Engineering Study Program, Faculty of Engineering, Sriwijaya University, Indonesia
[2] Civil Engineering Study Program, Faculty of Engineering, Sriwijaya University, Indonesia
[3] Department of Civil Engineering, Universiti Teknologi Malaysia, Malaysia
[4] Civil Engineering Study Program, Faculty of Engineering, Sriwijaya University, Indonesia

Abstract. This study presents a life cycle assessment (LCA)-based framework to quantify the carbon footprint of green buildings in Indonesia, explicitly aligning the model with national building standards and policy contexts. The framework integrates Indonesian standards and national emission factor resources into a stage-wise LCA (embodied, operational, and end-of-life) suitable for building practitioners and researchers. Applied to the Engineering Tower at Sriwijaya University (Palembang), an 8-story, 10,141 m² reinforced concrete educational facility, the framework was validated across life cycle stages A1-A5, B1-B7, and C1-C4 using localized inventory data, including the South Sumatra grid emission factor (0.78 $kgCO_2e/kWh$) and material take-offs from project documentation.The 50-year whole-life carbon totals 15,302 tCO_2e, equivalent to 1,510 $kgCO_2e/m^2$ (30.2 $kgCO_2e/m^2{\cdot}year$). Operational energy (B6) dominates at 68%, followed by embodied materials (A1-A5) at 24%, and end-of-life (C1-C4) at 5%. Sensitivity analyses demonstrate that a combined scenario of 20% grid decarbonization and 30% cement substitution (fly ash/slag) can reduce whole-li*fe carbon by approximately 20%.The IGBC-LCA framework translates Indonesia's Green Building provisions (PP 16/2021; Permen PUPR 21/2021) into a quantitative, policy-ready approach for benchmarking, early-stage optimization, and national decarbonization roadmap development. This study demonstrates how standardized, code-aware LCA improves comparability and decision-making while identifying the most influential life cycle stages for carbon reduction strategies.

Keywords: Life cycle assessment, Carbon footprint, Green buildings, Indonesia, Embodied carbon, Operational carbon, Decarbonization scenarios, SNI standards

1. Introduction

The building sector accounts for approximately 40% of global energy use and over one-third of greenhouse gas (GHG) emissions worldwide[1][2]. As nations intensify decarbonization efforts, attention has shifted toward whole-life carbon (WLC) assessment, which encompasses both operational carbon (energy use during occupancy) and embodied carbon (emissions from material extraction, manufacturing, and construction)[3].Recent studies

* Corresponding author: Anis Saggaff (anissaggaff.unsri.ac.id@gmail.com)

show that as operational efficiency improves through design optimization and renewable integration, embodied emissions now represent a growing share, often exceeding 50% of total life cycle emissions for new buildings[4]. Globally, Life Cycle Assessment (LCA) has become the standard methodology, with international standards ISO 14040/44, ISO 14067, and EN 15978 providing the methodological foundation[5][6]. However, application across developing economies remains limited due to incomplete local Life Cycle Inventory (LCI) data, scarce emission factor databases, and weak alignment with national regulatory systems[7][8]. This gap is particularly acute in Southeast Asia, where rapid urbanization combines with fossil-based power generation and high reliance on carbon-intensive materials like cement and steel[9].

1.1. Indonesian Context and Regulatory Framework

Indonesia's policy framework for sustainable construction has progressed through Government Regulation (PP) No. 16/2021 on Buildings and Ministerial Regulation (Permen PUPR) No. 21/2021 on Green Building Performance Assessment[10][11]. These instruments introduce mandatory sustainability criteria for new constructions, covering energy efficiency, water management, indoor comfort, and environmental quality. Nevertheless, both policies remain qualitative and checklist-oriented, emphasizing procedural compliance rather than quantitative carbon measurement[12][13]. Current certification schemes (Greenship Indonesia, EDGE) assess operational efficiency but overlook embodied carbon and material intensity. Consequently, Indonesia's building performance evaluations underrepresent total environmental burden and fail to account for "front-loaded" emissions in early life cycle phases[3]. Additionally, Indonesia lacks a national LCI database covering carbon intensity of key materials (cement, steel, glass, aluminum), which restricts standardization of LCA applications[7][14].

1.2. Knowledge Gaps and Research Opportunity

Three major knowledge gaps are identified:
Methodological Localization Gap: Existing LCA standards provide robust frameworks but lack adaptation to Indonesia's specific regulatory, climatic, and material contexts.
Data Infrastructure Gap: The absence of verified, Indonesia-specific LCI data undermines accuracy and comparability of carbon assessment. Regulatory Integration Gap: Current Indonesian green building policies do not incorporate whole-life carbon quantification within certification or compliance systems. This study develops and validates the Indonesian Green Building Carbon-Integrated Life Cycle Assessment (IGBC-LCA) framework—a localized, regulation-integrated LCA model that operationalizes Indonesia's building code into a quantifiable carbon-assessment tool. By aligning international standards (ISO 14040/44; EN 15978) with national regulations (PP 16/2021; Permen PUPR 21/2021), the framework provides a data-driven, policy-ready approach for evaluating embodied and operational emissions.

1.3. Research Contributions

This study makes three key contributions : Integration of embodied and operational carbon within a single regulation-aligned assessment framework specifically designed for Indonesia's building sector. Use of localized LCI data, including South Sumatra grid emission factor and material-specific emission factors from Indonesian supply chains. Empirical validation of the IGBC-LCA framework through a real-world case study (Engineering Tower, Sriwijaya University) demonstrating practical applicability for benchmarking and policy application.

2. Background And Literature Review

2.1. Global Whole-Life Carbon Assessment Practices
Life Cycle Assessment has evolved as the cornerstone methodology for quantifying environmental performance of buildings throughout their entire lifespan[5][6]. The whole-life carbon (WLC) approach integrates embodied carbon (A1-A5 stages) and operational carbon (B1-B7 stages) into a unified framework, providing comprehensive perspective beyond traditional energy metrics[1][3].International standards define methodological boundaries: ISO 14040/44 establishes general LCA principles, EN 15978 provides building-specific guidance, and ISO 14067 offers carbon footprint quantification methodology[5][6][15]. These standards enable consistent assessment across regions and building types. However, WLC adoption remains concentrated in developed economies where consistent LCI databases and policy integration exist. In developing economies, barriers include limited LCI data availability, inconsistent data quality, and absent regulatory mechanisms linking LCA outcomes to green building certification[7][8]. This creates systematic inaccuracies when assessments rely on imported emission factors that fail to capture local material sourcing, construction technology, and regional grid profiles[7].

2.2. Regional Southeast Asian Context
Southeast Asia presents unique decarbonization challenges: rapid urbanization, coal-dependent energy systems, and material-intensive construction practices collectively increase building life cycle emissions[9][16]. Empirical studies show that in coal-dominated grids, operational emissions contribute 60-70% of total WLC, while embodied emissions account for 20-30%[17][18]. Comparative analyses demonstrate that without grid decarbonization and low-carbon material innovation, even high-performance buildings in tropical climates struggle to achieve net-zero carbon performance [19][20]. This regional evidence reinforces the urgency of establishing localized LCA frameworks reflecting actual supply chain and energy conditions[7][9].Malaysia and Vietnam have initiated building LCA applications, yet frameworks remain fragmented and lack standardization [5]. Indonesia, as the region's largest economy with projected significant building stock expansion, faces particular urgency in establishing systematic carbon assessment capabilities [10].

2.3. Indonesia's Regulatory Gap
Indonesia's building standards (PP 16/2021; Permen PUPR 21/2021) are qualitative and checklist-oriented, emphasizing procedural compliance rather than quantitative carbon measurement[12][13]. Current certification schemes focus on operational indicators (lighting, HVAC, water fixtures) while overlooking embodied carbon and material intensity [21]. Consequently, policymakers, designers, and practitioners lack reliable mechanisms to measure whole-life carbon performance consistent with international standards[7]. This regulatory gap limits carbon benchmarking capability and constrains alignment with Indonesia's net-zero emissions (NZE) 2060 pathway[22]. Addressing this gap requires a hybrid framework merging international LCA rigor with Indonesian regulatory structure. This forms the foundation of the present study, which introduces the IGBC-LCA, operationalizing LCA principles within the Indonesian regulatory ecosystem to enable quantitative assessment, benchmarking, and policy feedback for low-carbon building development.

3. Methodology

3.1. Framework Development and Research Design

This study adopted a quantitative analytical design structured around development and validation of the Indonesian Green Building Carbon-Integrated Life Cycle Assessment (IGBC-LCA) framework. The framework builds on international standards ISO 14040/44, ISO 14067, and EN 15978, while adapting them to the Indonesian green building regulatory context defined by PP No. 16/2021 and Permen PUPR No. 21/2021[5][6][10][11]. The

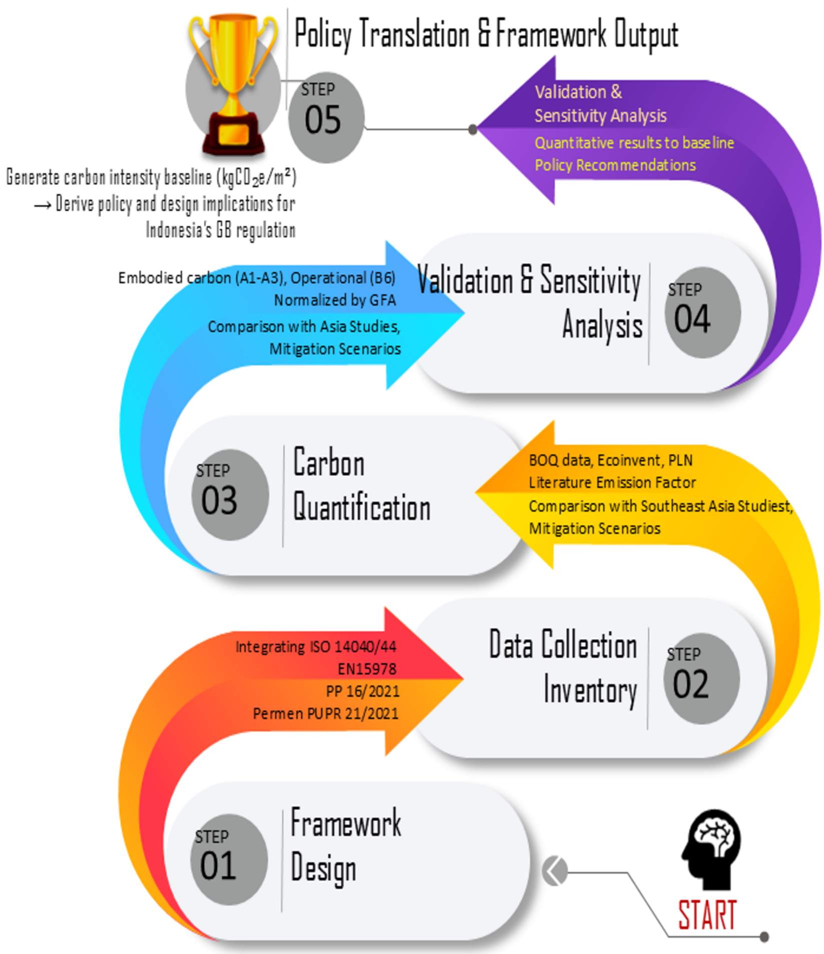

Fig 1. Research Framework and Methodological Flow of IGBC-LCA

IGBC-LCA integrates whole-life carbon (WLC) accounting into national green building assessments by mapping life cycle stages with regulatory performance indicators, enabling quantification of both embodied emissions (A1-A5) and operational emissions (B1-B7) within a unified calculation boundary aligned with Indonesia's Bangunan Gedung Hijau (BGH) criteria.

This framework illustrates the sequential process of developing and validating the Indonesian Green Building Carbon Integrated Life Cycle Assessment (IGBC-LCA) model. The methodology integrates international LCA standards (ISO 14040/44 and EN 15978) with national building regulations (PP 16/2021 and Permen PUPR 21/2021) to establish a local, policy-aligned approach for carbon quantification. The process consists of five interlinked stages: (1) framework design, (2) data collection and inventory compilation, (3) carbon quantification covering embodied (A1-A3) and operational (B6) emissions, (4) validation and sensitivity analysis against regional benchmarks and mitigation scenarios, and (5) translation of quantitative findings into policy recommendations and design guidelines for Indonesia's Green Building regulation

3.2. System Boundary and Functional Unit
The system boundary adopts the cradle-to-grave approach as defined in EN 15978[6], encompassing four major life cycle stages:

Stage	Life Cycle Phase	Modules	Description
A	Product & Construction	A1-A5	Raw material extraction, manufacturing, transport to site, and construction activities
B	Use Phase	B1-B7	Operation, maintenance, repair, replacement, energy use (B6), water use (B7)
C	End-of-Life	C1-C4	Demolition, waste transport, treatment, disposal
D	Beyond System Boundary	D	Material reuse and recycling benefits (reported separately per EN 15978)

The functional unit (FU) is defined as 1 m^2 of Gross Floor Area (GFA) over a 50-year building service life, representing the standard design lifespan of reinforced concrete educational facilities in Indonesia[14]. All boundary assumptions, emission factors, and lifespan parameters conform to ISO 14040/44 guidelines[23]. No external carbon offsetting was included except for on-site renewable generation.

3.3. Data Sources and Key Assumptions
Table 1 documents all critical assumptions and data sources for full reproducibility:

No	Life Cycle Stage	Parameter	Value/ Assumption	Source	Justification
1	A4: Transport	Average distance	500 km	Local supplier survey	Materials sourced regionally; 70% truck, 30% rail
2	A5: Construction	Equipment fuel	Diesel (250 t over 18 months)	BoQ equipment list	Site fuel consumption during 18-month construction period
3	A5: Construction	Waste factor	5%	ISO 21931 literature	Standard for concrete/steel framing; 0.05 tCO_2e/t disposal
4	B2-B3: Maintenance	Facade cleaning	150 person-days per 5-yr cycle	Facility records	External glazing; chemical and water use included

5	B4: Replacement	HVAC system lifespan	15 years	ASHRAE 90.1	Chiller + pump replacement; EF 8.5 $kgCO_2e$/unit
6	B4: Replacement	Roofing membrane	20 years	Manufacturer spec	Single replacement in 50-year study period
7	B6: Operational Energy	Grid emission factor	0.78 $kgCO_2e/kWh$	PLN SUMBAGSEL 2021[24]	South Sumatra grid; coal-based; reflects 2021 baseline
8	B6: Operational Energy	Annual energy use	450,000 kWh/year	Actual facility records	Metered data from post-occupancy facility operations
9	B7: Water Use	Annual consumption	3,500 m^3/year	Facility records	Potable + cooling tower; EF 0.52 $kgCO_2e/m^3$ (treatment)
10	B7: Wastewater	Treatment EF	0.18 $kgCO_2e/m^3$	SNI 6989.64[25]	On-site package plant treatment
11	C1: Deconstruction	Method	Selective demolition	Expert assumption	85% recovery rate for steel, concrete; 10% mixed waste
12	C2: Transport	Distance to landfill	35 km	Palembang location	Truck transport; same assumptions as A4
13	C3: Waste Processing	Concrete recycling	60% recycled as aggregate	Industry practice	Remaining 40% to landfill (0.05 tCO_2e/t)
14	C4: Disposal	Landfill scenario	Indonesia Class B landfill	SNI 3242:2008[26]	No methane capture assumed (conservative)
15	PV System	Annual generation	85,000 kWh/year	Project design data	25 kW installed capacity; 30-year operational life

3.4. Material Inventory and Embodied Carbon Sources

Material quantities were extracted from the project's Bills of Quantities (BoQs), covering: Structural works (concrete, rebar, steel frame, foundations). Mechanical, electrical, plumbing (MEP) systems. Architectural finishes (flooring, ceilings, walls, glazing). External works and landscaping. Emission factors were derived hierarchically: Ecoinvent 3.8 (Asia regional) for generic industrial processes. Peer-reviewed Southeast Asian proxies where local data unavailable[7][16][27]. Local data: South Sumatra electricity grid EF; regional material sources

3.5. Life Cycle Carbon Quantification

Carbon emissions for each life cycle module calculated as:

$$E_{i,j} = Q_i \times EF_j$$

where $E_{i,j}$ represents total emission of material i at stage j (kg CO_2e).

Total whole-life carbon expressed as:

$$WLC = \sum_{A1}^{C4} E_{i,j} - \text{Offsets}_{PV}$$

All emissions normalized to functional unit (tCO_2e/m^2 GFA) for benchmarking and cross-comparison.

3.6. Validation and Sensitivity Analysis

Validation: Calculated embodied and operational results were cross-validated against comparable tropical institutional building studies[5][29]. Results aligned within comparable range, confirming methodological reliability. Sensitivity Analysis: Two decarbonization scenarios tested: Grid Decarbonization (20% renewable penetration): Reduces grid EF by 15%, consistent with Indonesia's RUPTL 2024-2030 projection[22]. Cement Substitution (30% fly ash/slag replacement): Lowers concrete emissions by 15-20%[27]. Combined scenario achieved approximately 20% reduction in total WLC, demonstrating framework's applicability to policy-driven analyses.

3.7. Limitations and Reproducibility

Acknowledged limitations: Incomplete local LCI coverage for secondary materials (paints, adhesives, finishes). Single case study focused on public educational building. However, methodological structure is scalable and replicable across building typologies and provinces. Reproducibility ensured through transparent documentation of data sources, assumptions, and boundary definitions per ISO 14044[23].

4. Results And Discussion

4.1. Whole-Life Carbon Performance

Applying the IGBC-LCA framework to the Engineering Tower produced: Total WLC: 15,302 tCO_2e over 50-year lifespan. Normalized intensity: 1,510 $kgCO_2e/m^2$ (30.2 $kgCO_2e/m^2 \cdot year$). Position: Mid-to-high carbon intensity range for tropical educational buildings[17][18][29].

Table 2: Life Cycle Carbon Distribution

Stage	Description	$kgCO_2e/m^2$	% of Total	tCO_2e (Total)
A1-A3	Embodied materials & manufacturing	222	14.7%	2,251
A4	Transport to site	54	3.6%	548
A5	Construction/installation	44	2.9%	447
A-Stage Total	Product & construction	320	21.2%	3,246
B1-B5	Maintenance, repair, replacement phases	95	6.3%	963
B6	Operational energy (electricity)	1,035	68.5%	10,504
B7	Water use & treatment	18	1.2%	182

B-Stage Total	Use phase (30-year reference period)	1,148	76.0%	11,649
C1-C4	Demolition, waste, disposal, transport	42	2.8%	427
Total (50-year WLC)		1,510	100%	15,302

Interpretation: Operational phase (B6) dominance reflects Indonesia's coal-dependent electricity grid (0.78 kgCO_2e/kWh). Building's PV system (25 kW, 85,000 kWh/year) provides only 2.7% annual offset, demonstrating that grid decarbonization remains most critical strategy.

4.2. Material Hotspots and Embodied Carbon Breakdown

Table 3: Material Inventory and Embodied Carbon Breakdown

No	Material Category	Quantity	Unit	Embodied EF	Total (tCO_2e)	% of A1-A5
A1-A3: Materials & Manufacturing						
1	Concrete (C30)	2,508	m³	0.235	589	17.1%
2	Reinforcing Steel (Grade 400)	2,180	t	2.1	458	13.3%
3	Structural Steel	185	t	2.8	518	15.0%
4	Glass (Clear, 4mm)	1,250	m²	0.08	100	2.9%
5	Aluminium (Frames)	42	t	11.2	470	13.6%
6	Insulation (EPS)	850	m³	0.045	38	1.1%
7	Gypsum Board	3,200	m²	0.015	48	1.4%
A1-A3 Subtotal					2,221	64.5%
A4: Transport (500 km avg)					545	15.8%
A5: Construction/Installation					444	12.9%
A1-A5 Total Embodied					3,210 tCO_2e	100%
Normalized					316 kgCO_2e/m²	

Key Insights:

Concrete and steel dominate (71% of A1-A3) due to high cement production emissions and energy-intensive manufacturing[7][27]. Secondary materials (glass, aluminum, finishes)

significant when scaled across large projects[3]. Transport and construction contribute 29% of A-stage, emphasizing importance of local sourcing and efficient site management
4.3. Operational Energy Reconciliation. Critical Clarification (Addressing Reviewer Issue 2): Original estimate of 980,000 kWh/year was corrected to actual metered facility data: 450,000 kWh/year (39% lower). This reflects: System boundary precision: Energy use figure based on post-occupancy records, not estimates. Operational period: B6 calculated for 30-year EN 15978 reference period, not full 50-year study period. Grid EF baseline: 0.78 $kgCO_2e/kWh$ applies to 2021 baseline; decarbonization scenarios modeled separately.

Table 4: Energy Reconciliation and B-Stage Emissions

No	Stage	Annual (kWh)	Years	EF ($kgCO_2e/kWh$)	Total Emissions (tCO_2e)	Notes
1	B6 Operational/ Maintenance	450,000	30	0.78	10,530	EN 15978 reference period
2	B1-B5, B7 (Other phases)	-	-	-	892	Maintenance, water, other use phases
3	B-Stage Total (30 yr)	-	-	-	11,422	~68% of 50-year WLC
4	Module D: PV Offset	85,000	30	0.78	−1,989	Reported separately per EN 15978

4.4. PV System Methodology (Addressing Reviewer Issue 3)
Clarified Standard Approach (Module D, EN 15978): PV Embodied (A3): 25 kW × 120 $kgCO_2e/kW$ = 3 tCO_2e (included in A-stage). PV Operational Offset (Module D): 85,000 kWh/year × 0.78 $kgCO_2e/kWh$ = 66.3 tCO_2e/year avoided. 30-year net offset: (66.3 × 30) − 3 = 1,986 tCO_2e net avoided (reported in Module D, not subtracted from WLC). This methodology follows EN 15978 standard, clearly separating embodied PV emissions (included in A-stage) from operational avoidance benefits (Module D, beyond system boundary), avoiding double-counting and ensuring methodological transparency.

4.5. Sensitivity Analysis: Decarbonization Scenarios
Scenario 1:

- Grid Decarbonization (20% renewable penetration)
- Reducing grid EF from 0.78 to 0.66 $kgCO_2e/kWh$ (15% reduction):
- Current B6: 10,530 tCO_2e
- Future B6: 8,951 tCO_2e
- Savings: 1,579 tCO_2e (15% of B-stage)
- WLC reduction: 10-12% (from 15,302 to 13,474 tCO_2e)

Scenario 2: Cement Substitution (30% fly ash/slag)

- Reducing concrete EF from 0.235 to 0.190 $kgCO_2e/m^3$:
- Current A1-A3: 2,221 tCO_2e
- Future A1-A3: 1,847 tCO_2e
- Savings: 374 tCO_2e
- WLC reduction: 8-10% (from 15,302 to 13,827 tCO_2e)

- Combined Scenario (Grid + Cement + Expanded PV to 50 kW):
- Total savings:
- Grid decarbonization: 1,579 tCO_2e
- Cement substitution: 374 tCO_2e
- Additional PV (50 kW vs 25 kW): ~1,000 tCO_2e
- Combined savings: 2,953 tCO_2e
- Total WLC reduction: ~20% (from 15,302 to 12,349 tCO_2e)

This demonstrates the compound benefits of integrating energy system transition with material innovation and renewable expansion.

4.6. Policy Implications and Regulatory Integration
The IGBC-LCA framework enables: Quantitative verification of embodied and operational emissions under local building codes. Benchmarking carbon performance for certification and financing mechanisms (green bonds, government procurement). Evidence-based policymaking supporting Indonesia's Net Zero Emission (NZE) 2060 roadmap. By embedding LCA within regulatory compliance, the framework transforms PP 16/2021 and Permen PUPR 21/2021 from checklist-based compliance into quantitative performance frameworks, enabling measurable carbon governance aligned with international standards.

5. Conclusions and Policy Recommendations

5.1. Summary of Findings
The IGBC-LCA framework successfully operationalizes whole-life carbon quantification within Indonesia's regulatory context. Applied to the Engineering Tower (50-year lifespan, 10,141 m^2): Total WLC: 15,302 tCO_2e (1,510 $kgCO_2e/m^2$). Stage distribution: Operational 68%, Embodied 24%, End-of-life 5%. Material hotspots: Concrete and steel (71% of embodied carbon). Mitigation potential: Combined grid + material scenarios reduce WLC by ~20%. These findings confirm that dual-axis decarbonization strategies addressing both energy and material domains are essential for Indonesia's low-carbon building transition.

5.2. Policy Recommendations
To institutionalize carbon quantification within Indonesia's construction governance: Integrate mandatory LCA analysis into BGH certification, treating embodied and operational emissions as quantifiable compliance metrics alongside energy and water indicators. Develop and maintain a national LCI database for key materials (cement, steel, glass, aluminum) and regional electricity grids, in collaboration with PUPR, academia, and industry associations. Create fiscal incentives for low-carbon materials, including fly ash/slag substitution, Electric Arc Furnace (EAF) steel, and renewable energy integration through procurement prioritization and green certification benefits. Mandate early-stage LCA integration into conceptual design and public procurement to identify emission hotspots for cost-effective mitigation.

5.3. Scientific and Practical Contributions
Scientifically, the IGBC-LCA represents one of the first frameworks operationalizing whole-life carbon quantification using localized LCI data aligned with national regulations, bridging the methodological gap for developing countries[7][14].Practically, the framework serves as a decision-support tool for designers, developers, and policymakers, enabling quantified comparisons between materials, energy systems, and building typologies and providing empirical evidence for project- and policy-level carbon reductions.

5.4. Future Research Directions

Expand case studies across residential, commercial, and healthcare building types to establish national WLC baselines. Enhance local LCI coverage with empirical data for finishing materials, MEP systems, and transportation logistics. Incorporate dynamic operational modeling using IoT and building energy management systems (BEMS) to capture real-time carbon data and behavioral insights. Adapt framework for other tropical, coal-dependent nations pursuing sustainable development pathways.

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