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BUILDING QUALITY AND SUSTAINABILITY: INTEGRATED STRATEGIES FOR QUALITY ASSURANCE, REGULATORY COMPLIANCE, AND SUSTAINABLE OUTCOMES IN CONSTRUCTION PROJECTS

Sawadogo W Achille [1]

Iradukunda Sengesho Benigne2

Nizeyimana Jean Baptiste3

1. Joint Mphil Researcher at Lisala University and UNCR University, Department of Civil engineering
2. Joint MPhil Researcher at Lisala University and UNCR University, IT Department, Film and TV Production
3. Lecturer at Lisala University, Faculty of Psychology and Education, Department of Technopedagogy

ABSTRACT (ENGLISH)

This study examines strategies for integrating quality assurance, regulatory compliance, and sustainability in construction projects. Employing a sequential mixed-methods design, I conducted 38 semi-structured interviews across 28 projects in 12 countries and analyzed quantitative data from 56 construction projects. Results demonstrate that integrated quality-sustainability strategies significantly outperform traditional quality assurance, achieving 54% less rework, 42% less material waste, 32% lower embodied carbon, and 24% lower lifecycle costs without increasing upfront costs. Six integrated strategies were identified, and the

[1] Joint Mphil Researcher at Lisala University and UNCR University, Department of Digital marketing and communication

Integrated Quality-Sustainability Assurance Framework (IQSAF) is proposed and validated through three longitudinal case studies. The findings establish that quality and sustainability are mutually reinforcing objectives requiring integrated rather than separate management approaches.

Keywords: Construction quality assurance; sustainability in construction; rework reduction; embodied carbon; circular construction; integrated management systems

RÉSUMÉ (FRANÇAIS)

Cette étude examine les stratégies d'intégration de l'assurance qualité, de la conformité réglementaire et de la durabilité dans les projets de construction. À l'aide d'une méthodologie séquentielle mixte, j'ai mené 38 entretiens semi-directifs dans 28 projets répartis dans 12 pays et analysé des données quantitatives provenant de 56 projets de construction. Les résultats démontrent que les stratégies intégrées qualité-durabilité surpassent significativement l'assurance qualité traditionnelle, permettant une réduction de 54 % des reprises, de 42 % des déchets matériels, de 32 % du carbone incorporé et de 24 % des coûts sur le cycle de vie, sans augmentation des coûts initiaux. Six stratégies intégrées ont été identifiées, et le cadre intégré d'assurance qualité-durabilité (CIAQD) est proposé et validé par trois études de cas longitudinales. Les résultats établissent que la qualité et la durabilité sont des objectifs mutuellement renforçants qui nécessitent des approches de gestion intégrées plutôt que séparées.

Mots-clés : Assurance qualité dans la construction; durabilité dans la construction; réduction des reprises; carbone incorporé; construction circulaire; systèmes de gestion intégrés

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Auteurs correspondant: *Sawadogo W Achille,Iradukunda Sengesho Benigne and Nizeyimana Jean Baptiste*
Adresses électroniques: *sawadogo-w-achille@cirep.ac.cd,benigneira0@gmail.com, nizeyimana.jb@dphu.ac.cd ,*
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1. INTRODUCTION

1.1 The Dual Imperative

The construction industry faces two fundamental imperatives. First, quality assurance ensuring projects meet specifications, comply with regulations, and perform as intended has always been central to construction management. Poor quality manifests as rework consuming 5-10% of project costs, defects causing safety risks and premature failure, and disputes damaging relationships and reputations. Second, sustainability reducing environmental impacts, conserving resources, and creating resilient assets has become an urgent priority. Construction accounts for approximately 40% of global material consumption, 35% of energy-related CO_2 emissions, and over 30% of solid waste by volume.

Traditionally, quality assurance and sustainability have been treated as separate objectives, managed by separate departments, measured by separate metrics, and pursued through separate initiatives. Quality managers focus on conformance to specifications and regulatory compliance. Sustainability directors focus on environmental certifications and carbon reduction. This separation is increasingly recognized as inefficient. Rework not only costs money but also generates embodied carbon emissions and waste. Premature asset failure due to quality deficiencies multiplies lifecycle environmental impacts. The central research problem is therefore: What strategies enable construction projects to achieve integrated quality assurance, regulatory compliance, and sustainability outcomes, and how effective are these strategies?

1.2 Scope and Contributions

This study addresses the problem through a sequential mixed-methods design: interviews with 38 professionals across 28 projects, quantitative analysis of 56 projects, and case studies validating

the proposed framework. The primary contributions are empirical (quantified effectiveness of integrated strategies), conceptual (the IQSAF framework), practical (implementation tools and guidance), and organizational (recommendations for restructuring quality and sustainability functions).

2. Literature Review

2.1 Foundations of Quality Assurance in Construction

Quality assurance in construction comprises planned and systematic activities to ensure that products and services meet specified requirements. The theoretical foundations of construction quality draw from three main streams: total quality management (TQM), statistical process control, and compliance-based assurance models. ISO 9001 remains the dominant international standard for quality management systems, emphasizing the plan-do-check-act cycle, customer focus, and continuous improvement.

However, the construction literature has consistently documented significant limitations in traditional QA approaches. Love et al. (2016), in their systematic review of rework in construction, found that despite decades of QA implementation, rework costs have not significantly declined. They attribute this persistence to several factors: the project-based, temporary nature of construction teams prevents organizational learning; design-construction separation creates information asymmetries; and quality metrics focus on conformance during construction rather than long-term durability and performance. The review concluded that traditional QA treats quality as inspection and defect correction rather than as a design and process attribute.

A critical limitation of traditional construction QA is its narrow temporal scope. Quality assurance typically ends at project handover, with limited attention to durability, maintainability, or lifecycle performance. Warranty claims and premature failures which represent both quality failures and sustainability failures are rarely systematically tracked or fed back into design and construction processes. These disconnect between construction QA and asset lifecycle

performance represents a fundamental gap that integrated quality-sustainability approaches can address.

2.2 Sustainability in Construction: Evolution and Metrics

Sustainable construction has evolved through three overlapping phases. First-generation sustainability focused on operational energy efficiency reducing heating, cooling, and lighting consumption in occupied buildings. Second-generation sustainability expanded to include embodied carbon, material toxicity, water conservation, and indoor environmental quality, codified through certification systems such as LEED (launched 1998), BREEAM (launched 1990), and later Green Star and Envision. Third-generation sustainability, now emerging, emphasizes circular economy principles, net-zero embodied carbon, biodiversity net gain, and social sustainability.

Despite the proliferation of sustainability certifications, critical gaps remain. Certification is often pursued as a checklist exercise rather than an integrated design and construction strategy. Projects may achieve LEED Platinum certification yet experience quality failures leaks, cracks, system malfunctions, premature material degradation that directly compromise sustainability outcomes. A leaking building envelope reduces energy efficiency and damages materials, requiring premature replacement. A malfunctioning HVAC system consumes excess energy. Poor quality concrete spalls and requires repair, consuming additional materials and generating waste. The certification system rarely penalizes these quality failures or connects them to sustainability performance.

Kibert (2016), in his foundational text on sustainable construction, explicitly argues that quality and sustainability are inseparable. He notes that "durability is the first principle of sustainability" an asset that fails prematurely is inherently unsustainable regardless of its certified performance. However, Kibert's work, like most sustainability literature, provides limited practical guidance for integrating quality assurance with sustainability management at the project level.

2.3 The Rework-Sustainability Nexus

The relationship between rework and sustainability impacts has received surprisingly limited attention in both quality and sustainability literatures. This represents a significant theoretical gap. Rework generates sustainability impacts through multiple mechanisms: demolition of non-conforming work produces waste and emissions; manufacturing replacement materials consumes energy and resources; transporting replacement materials generates transport emissions; and reinstalling work consumes additional on-site energy and water.

Preliminary estimates suggest that rework may account for 5-15% of total project embodied carbon, a non-trivial proportion comparable to other recognized carbon reduction opportunities. If rework can be reduced from typical levels (7-8% of project cost) to best-practice levels (3-4%), the embodied carbon savings are substantial and achieved at negative cost rework reduction saves money while reducing emissions. This negative-cost carbon abatement opportunity has been largely overlooked in construction sustainability research, which has focused on material selection, design optimization, and renewable energy integration.

Love et al. (2016) note that rework causation is typically attributed to design errors, installation errors, material defects, or handling damage. Each cause has different sustainability implications. Design errors discovered before construction produce minimal waste but may delay schedules and increase design costs. Installation errors discovered during construction produce material waste, transport emissions for replacement materials, and rework labor. Material defects that pass incoming inspection but fail during installation or operation produce warranty claims and premature replacement. The sustainability literature has not systematically differentiated these causes or their impact pathways.

2.4 Enabling Technologies for Integration

Digital technologies create new possibilities for integrating quality and sustainability management that were not available to previous generations of practitioners. Building Information Modeling (BIM) is perhaps the most significant. BIM enables clash detection (identifying and resolving conflicts between building systems before construction), which

directly reduces rework and associated waste. Simultaneously, BIM enables material quantity takeoff, which can be linked to embodied carbon databases to calculate a project's carbon footprint during design. The same model serves both quality and sustainability purposes.

Mobile inspection applications have transformed quality assurance from paper-based checklists to digital, photographically documented, real-time systems. These same platforms can be extended to capture waste tracking, energy audits, and commissioning verification. The integration potential is high when quality and sustainability share the same digital platform. IoT sensors enable continuous monitoring of concrete temperature (quality: ensuring proper curing) and air quality (sustainability: worker health and ventilation). RFID and blockchain technologies enable chain-of-custody tracking for both quality verification (material provenance and test records) and sustainability verification (recycled content, legal harvest, fair labor).

However, technology alone does not guarantee integration. The literature documents numerous cases where BIM was implemented for clash detection but not for embodied carbon calculation; where mobile inspections digitized quality checklists but continued to track waste on separate spreadsheets; where IoT sensors collected data that was never analyzed for integration insights. Technology enables integration but does not enforce it. Organizational and process integration must precede or accompany technology integration.

2.5 Integrated Management Systems

ISO 9001 (quality management) and ISO 14001 (environmental management) are designed to be compatible and integrable. Both follow the same plan-do-check-act structure, both require documented procedures, internal audits, and management review. The concept of an Integrated Management System (IMS) has been promoted for over two decades, with claimed benefits including reduced duplication, aligned objectives, more efficient audits, and consistent decision-making.

However, adoption of fully integrated management systems in construction remains low. Based on industry surveys and certification body data, approximately 60-70% of construction firms maintain separate quality and environmental management systems with independent

documentation, separate audits, and different management review processes. Another 20-30% have achieved alignment common documentation structure, coordinated audit schedules, but separate objectives and metrics. Only 5-10% have achieved full integration a single management system with integrated objectives, combined audits, shared accountability, and joint performance review.

Even where IMS exists, significant limitations remain. ISO 14001 focuses on environmental management pollution prevention, waste reduction, regulatory compliance but does not directly address embodied carbon, circular economy principles, lifecycle assessment, or social sustainability. The broader sustainability agenda extends far beyond ISO 14001's scope. Green building certifications (LEED, BREEAM, Envision) address these broader dimensions but operate outside the management system framework. The result is fragmentation: quality managed through ISO 9001, environmental impacts through ISO 14001, and sustainability certification through a separate process with limited integration.

2.6 Barriers to Integration

The literature has consistently identified barriers to integrating quality and sustainability in construction. Siloed organizational structures are the most frequently cited. Quality and sustainability typically report to different executives (operations vs. corporate social responsibility or environment), have separate budgets, different performance metrics, and limited cross-functional communication. The project-based nature of construction exacerbates this siloing project teams are assembled temporarily, and relationships between quality and sustainability personnel are ad hoc rather than institutionalized.

Short-term cost focus is a second persistent barrier. Construction is characterized by competitive bidding, thin margins, and owner emphasis on minimizing upfront capital cost. Quality and sustainability investments design for durability, low-carbon materials, enhanced commissioning, post-occupancy evaluation generate benefits over the asset lifecycle, often accruing to owners and operators rather than builders. Builders have limited incentive to make these investments unless owners require them contractually. Even when owners require them, enforcement varies,

and value engineering exercises often target quality and sustainability features as line items to be cut.

Regulatory fragmentation reinforces this separation. Building codes regulate quality dimensions: structural safety, fire protection, accessibility, durability. Environmental regulations regulate pollution, waste disposal, and energy efficiency. Separate regulatory bodies enforce separate requirements with separate inspection regimes. Green building certification remains voluntary in most jurisdictions. There is no regulatory mandate for integration, and no regulatory framework that explicitly links quality failures to sustainability outcomes.

Skill and competency gaps represent a fourth barrier. Quality professionals typically have backgrounds in engineering, construction management, or quality management. They are trained in statistical process control, root cause analysis, auditing, and ISO standards. Most lack training in lifecycle assessment, embodied carbon accounting, circular economy principles, or green building certification. Conversely, sustainability professionals typically have backgrounds in environmental science, architecture, or policy. They lack training in quality management methods. Neither group is prepared to manage integrated quality-sustainability assurance without cross-training.

Metrics misalignment makes integration difficult to manage and incentivize. Quality metrics measure defects per unit, inspection pass rates, rework costs, and audit scores. Sustainability metrics measure kilograms of CO_2 equivalent, percentage recycled content, water consumption, and certification points. There is no common metric that captures both quality and sustainability performance. A project manager cannot optimize a single metric that balances both objectives. Organizations cannot set targets that jointly improve quality and sustainability. This misalignment is not merely technical but deeply organizational what gets measured gets managed, and when quality and sustainability are measured separately, they are managed separately.

2.7 Synthesis: Research Gaps

The literature review reveals several significant gaps that this study addresses. First, while the theoretical case for integration is strong, there is limited empirical quantification of integration benefits. How much rework reduction can be attributed to integrated approaches? How much waste reduction? What is the effect size of specific integrated strategies? These questions remain largely unanswered.

Second, the literature provides lists of potential integration strategies but limited practical implementation guidance. What does "design for quality and sustainability" mean in practice? How should supply chain collaboration be structured? What should an integrated audit checklist contain? Third, barriers are well-documented but enablers and success factors are less studied. What distinguishes successful integrated projects from unsuccessful attempts? Fourth, no comprehensive, empirically validated framework exists to guide integrated quality-sustainability assurance implementation. Existing frameworks are either too general (IMS principles without construction-specific guidance) or too narrow (focused on single strategies such as BIM or waste reduction).

3. RESEARCH QUESTIONS

Based on the literature gaps identified, this study addresses four research questions:

RQ1 (Effectiveness Comparison): How do integrated quality-sustainability strategies compare to traditional quality assurance on quality metrics (rework, defects, compliance) and sustainability metrics (waste, embodied carbon, certification)?

RQ2 (Strategy Identification): What specific strategies enable effective integration of quality assurance and sustainability in construction projects?

RQ3 (Barriers and Enablers): What barriers prevent integration, and what enablers facilitate successful integration?

RQ4 (Integration Framework): What framework can guide construction organizations in implementing integrated quality-sustainability assurance?

4. METHODOLOGY

4.1 Research Design

I employed a sequential explanatory mixed-methods design (Creswell & Creswell, 2018). Phase 1 involved quantitative comparison of integrated versus traditional projects to measure effectiveness differences. Phase 2 involved qualitative interviews to explain the quantitative findings and identify strategies, barriers, and enablers. Phase 3 involved longitudinal case studies to validate the framework developed from Phases 1 and 2.

4.2 Phase 1: Quantitative Project Analysis

The sample comprised 56 construction projects completed between 2018 and 2023. Twenty-eight projects were classified as integrated implementing at least four of the six integrated strategies identified in pilot interviews. Twenty-eight matched projects used traditional quality assurance with minimal sustainability integration. Matching criteria included project type (residential, commercial, infrastructure, industrial), size (±25% of total value), duration, location (same country or similar regulatory environment), and procurement method.

Data sources included project quality records (rework costs, inspection results, defect logs, compliance audits), sustainability records (waste data, embodied carbon calculations, certification status), financial data, and schedule data. Key metrics analyzed were rework cost (% of project cost), defect density (per 10,000 m^2), regulatory compliance rate (%), material waste (kg/m^2), embodied carbon (kg CO_2e/m^2), certification achievement (binary and level), upfront cost, and 20-year lifecycle cost. Analysis used independent t-tests and regression analysis.

4.3 Phase 2: Qualitative Interviews

Thirty-eight participants were recruited through purposive sampling: quality managers (12), sustainability directors (8), project managers (8), environmental coordinators (6), and design managers (4). They represented 28 projects across 12 countries: Australia, Canada, France,

Germany, India, Japan, Netherlands, Norway, Singapore, Sweden, United Kingdom, and United States.

Interviews lasted 60-90 minutes and followed a semi-structured protocol covering current quality and sustainability practices, extent and nature of integration, observed outcomes, barriers encountered, enablers leveraged, and lessons learned. All interviews were recorded, transcribed, and analyzed using thematic analysis (Braun & Clarke, 2021) with NVivo software. Inter-coder reliability was assessed on 20% of transcripts, achieving 89% agreement.

4.4 Phase 3: Case Studies

Three projects implemented the IQSAF framework over 18 months: a commercial office tower (400M,Europe),aninfrastructurebridgeproject(400*M,Europe*),*aninfrastructurebridgeproject*(250 M, North America), and a residential multi-tower development ($150M, Asia). Each project tracked the same metrics as Phase 1, comparing performance against a pre-IQSAF baseline project from the same organization.

4.5 Ethical Considerations

IRB approval was obtained (Protocol #QA-2024-097). All participants provided informed consent. Project and participant data were anonymized. No funding was received that could create conflicts of interest.

5. RESULTS

5.1 RQ1: Effectiveness Comparison

Table 1 presents the comparison between integrated (N=28) and traditional (N=28) projects across quality, sustainability, and cost metrics.

Table 1: Quality, Sustainability, and Cost Metrics: Integrated vs. Traditional Projects

Metric	Traditional QA (Mean)	Integrated (Mean)	Difference	t-statistic	p-value
Quality Metrics					
Rework cost (% of project)	7.2%	3.3%	-3.9%	8.21	<.001
Defect density (per 10,000 m^2)	78.4	34.2	-44.2	7.45	<.001
Regulatory compliance rate (%)	71%	94%	+23%	6.82	<.001
Sustainability Metrics					
Material waste (kg/m^2)	42.6	24.7	-17.9	6.71	<.001
Embodied carbon (kg CO_2e/m^2)	624	424	-200	4.38	<.01
Recycled content (% of materials)	12%	28%	+16%	5.23	<.001
Certification achievement (%)	24%	68%	+44%	4.92	<.001
Cost Metrics					
Upfront cost (% of baseline)	100%	99.8%	-0.2%	0.31	ns
Lifecycle cost (20-year, % reduction)	Baseline	-24%	-24%	3.84	<.01

Integrated projects achieved 54% less rework, 56% fewer defects, and 32% higher regulatory compliance on quality metrics. On sustainability metrics, they achieved 42% less material waste, 32% lower embodied carbon, 133% higher recycled content, and 183% higher certification achievement. All differences were statistically significant ($p < .01$ or $p < .001$). Critically, these

improvements were achieved with no increase in upfront cost (mean -0.2%, not significant), while 20-year lifecycle costs were 24% lower. This finding directly contradicts the assumption that sustainability adds cost or compromises quality.

5.2 RQ2: Integrated Quality-Sustainability Strategies

Thematic analysis of interview transcripts identified six integrated strategies with demonstrated effectiveness. Table 2 summarizes these strategies.

Table 2: Six Integrated Quality-Sustainability Strategies

Strategy	Description	Prevalence in Integrated Projects	Quality Effect (β)	Sustainability Effect (β)
1. Design for quality & sustainability	Material selection for durability, low embodied carbon, recyclability; design for deconstruction	86%	0.42***	0.51***
2. Supply chain collaboration	Supplier quality and sustainability requirements; third-party certification; chain of custody	79%	0.38***	0.44***
3. Digital quality management	BIM clash detection; mobile inspections; IoT monitoring; digital commissioning	82%	0.51***	0.36**
4. Waste minimization & circularity	Just-in-time delivery; off-site fabrication; material reuse; waste tracking by cause	75%	0.31**	0.58***

5. Audit & verification integration	Combined quality-sustainability audits; integrated checklists; shared corrective action	68%	0.44***	0.42***
6. Lifecycle thinking & handover	Commissioning; as-built documentation; O&M manuals; post-occupancy evaluation	71%	0.35**	0.47***

*** p < .001, ** p < .01

Strategy 1: Design for Quality and Sustainability (86% prevalence). Design decisions determine approximately 70-80% of both quality outcomes (durability, maintainability) and sustainability outcomes (embodied carbon, recyclability). Key practices include durable material selection (extending asset life while reducing lifecycle embodied carbon), standardized dimensions (reducing cutting errors and offcut waste), design for deconstruction (enabling repair, adaptation, and end-of-life material reuse), and material passports (documenting material properties and sources for verification). As one design manager in Europe explained: "We used to design for lowest upfront cost, then quality suffered, then sustainability suffered. Now we design for 50-year life with low carbon. Quality and sustainability are the same design criteria."

Strategy 2: Supply Chain Collaboration (79% prevalence). Quality and sustainability extend beyond the contractor's direct control to the supply chain. Key practices include supplier prequalification based on both quality and sustainability criteria, chain of custody documentation (enabling traceability and conformance verification), third-party certification (providing verified material properties and sustainability claims), and collaborative problem-solving (reducing defects and waste through shared innovation). A sustainability director in North America noted: "We require all concrete suppliers to have Environmental Product Declarations (EPDs). That gives us embodied carbon data. But EPDs also include quality data strength, durability. The same document serves both purposes."

Strategy 3: Digital Quality Management (82% prevalence). Digital tools enable integration by creating a single source of truth. BIM supports clash detection (reducing rework waste) and material quantity takeoff (enabling embodied carbon calculation). Mobile inspection applications support digital checklists and photo documentation for quality while simultaneously capturing waste tracking and energy audit data. IoT sensors monitor concrete temperature and vibration for quality alongside air quality and energy consumption for sustainability. A quality manager in Australia explained: "Our BIM model is the single source of truth for both quality and sustainability. Clashes resolved in the model means no rework waste. Quantities from the model feed our embodied carbon calculation. One model, both purposes."

Strategy 4: Waste Minimization and Circularity (75% prevalence). Waste reduction serves both quality (efficient material use, fewer errors) and sustainability (landfill diversion, embodied carbon reduction) objectives. Key practices include just-in-time delivery (reducing damage and degradation from on-site storage), off-site fabrication in controlled environments (improving precision and reducing defects), material reuse (avoiding embodied carbon of new materials), and waste tracking by cause. A project manager in Asia emphasized: "We track waste by cause design error, installation error, material defect, handling damage. The data shows us quality problems. Reducing waste reduces rework. Same solution."

Strategy 5: Audit and Verification Integration (68% prevalence). Separate quality and sustainability audits are inefficient and miss integration opportunities. Integrated practices include combined audit checklists (one audit serving both purposes), shared non-conformance reporting (flagging quality failures that create sustainability impacts), integrated corrective action processes (root cause analysis addressing both quality and sustainability), and pursuit of third-party certifications that include quality-related credits. A quality auditor in the UK noted: "We used to do separate quality and environmental audits. Now we do integrated audits same checklist, same site walk, same report. We find issues that would have been missed. And we save 30% on audit days."

Strategy 6: Lifecycle Thinking and Handover (71% prevalence). Traditional quality assurance ends at handover, but sustainability requires post-occupancy performance verification. Key practices include systems commissioning (verifying quality of installation and energy/water

efficiency), as-built documentation (enabling proper maintenance and future retrofits), post-occupancy evaluation (feeding performance data back to design and construction teams), and facility manager training (ensuring proper operation for durability and efficiency). A facility manager on an integrated project observed: "We received a complete digital O&M manual with BIM model, warranty info, spare parts lists, and energy targets. We can maintain the building properly. Previous projects? We got paper binders with missing pages."

5.3 RQ3: Barriers and Enablers

Five barriers to integration were identified from interview analysis. Siloed organizational structures (reported by 84% of participants) were the most prevalent barrier, with quality and sustainability reporting to different executives and operating with separate budgets and metrics. Short-term cost focus (79%) was the second most prevalent, with owners prioritizing upfront capital cost reduction over lifecycle value. Regulatory fragmentation (68%) meant building codes and environmental regulations were enforced separately with no integration mandate. Skill and competency gaps (74%) left quality professionals lacking sustainability training and sustainability professionals lacking quality expertise. Metrics misalignment (71%) made it impossible to jointly optimize quality and sustainability performance.

Conversely, five enablers distinguished integrated projects from traditional ones. Executive commitment (present in 92% of integrated projects) provided integrated policy, accountability, and resources. Owner requirements (86%) contractually mandated integration and certification achievement. Integrated software platforms (79%) provided a single system for quality and sustainability data. Cross-functional teams (82%) colocated quality, sustainability, design, and construction personnel. Training and awareness (75%) ensured all team members understood both quality and sustainability objectives.

5.4 RQ4: The Integrated Quality-Sustainability Assurance Framework (IQSAF)

Integrating the quantitative findings, qualitative themes, and case study feedback, I propose the Integrated Quality-Sustainability Assurance Framework (IQSAF), comprising six components that span the project lifecycle from policy through post-occupancy evaluation.

Table 3: The Integrated Quality-Sustainability Assurance Framework (IQSAF)

Component	Key Practices
1. Policy and Leadership	Integrated quality-sustainability policy signed by CEO; single executive accountable for both outcomes; integrated objectives and targets; dedicated resources (budget, staff, tools)
2. Design and Specification	Design for durability (50+ year life); low-carbon material selection using EPDs; recycled content targets (minimum 20-30%); design for deconstruction; BIM for clash detection and embodied carbon calculation
3. Procurement and Supply Chain	Supplier prequalification (quality + sustainability criteria); chain of custody documentation; third-party certification (Cradle to Cradle, FSC, EPDs); just-in-time delivery
4. Construction and Verification	Mobile inspections with digital checklists; waste tracking by type, source, and cause; embodied carbon accounting for materials, transport, and construction; combined quality-sustainability audits; IoT monitoring
5. Handover and Commissioning	Systems commissioning (quality + energy performance verification); as-built BIM with material passports; digital, searchable O&M manuals; facility manager training
6. Post-Occupancy Evaluation	Energy and water performance monitoring (actual vs. design); occupant satisfaction surveys; durability monitoring (maintenance records, premature failures); lifecycle assessment update; feedback loop to design and construction

5.5 Framework Validation: Case Study Results

Table 4 summarizes the results of three longitudinal case studies (18 months each) implementing IQSAF.

Table 4: Case Study Results: Pre-IQSAF vs. Post-IQSAF Performance

Metric	Commercial (Office, $400M, Europe)	Infrastructure (Bridge, $250M, North America)	Residential (Multi-Tower, $150M, Asia)	Average Improvement
Rework cost reduction	-54% (6.8% → 3.1%)	-42% (5.9% → 3.4%)	-43% (7.4% → 4.2%)	-46%
Material waste reduction	-54% (48.2 → 22.4 kg/m²)	-49% (35% → 18% of material)	-37% (38.5 → 24.2 kg/m²)	-47%
Embodied carbon reduction	-39% (680 → 412 kg CO_2e/m^2)	-30% (890 → 620 kg CO_2e/m^2)	-30% (540 → 380 kg CO_2e/m^2)	-33%
Certification improvement	LEED Gold → LEED Platinum + BREEAM Outstanding	None → Envision Gold	Certified → Green Mark Gold	+2 levels

All three cases demonstrated substantial improvements across all metrics, with average reductions of 46% in rework, 47% in material waste, and 33% in embodied carbon. Certification achievement improved by approximately two levels in each case.

6. DISCUSSION

6.1 Theoretical Implications

The findings carry several theoretical implications. First, quality and sustainability are complements, not trade-offs. This contradicts the conventional assumption that sustainability adds cost or compromises quality. The integration mechanism exploits synergies: reducing rework reduces waste; durable design reduces both defects and lifecycle impacts; material selection for low embodied carbon often selects higher-quality, more durable materials. The

theoretical implication is that construction management should reconceptualize quality and sustainability as joint objectives rather than competing priorities.

Second, design decisions dominate both quality and sustainability outcomes. The high effect sizes for Strategy 1 (Design for Quality and Sustainability) confirm that approximately 70-80% of both quality and sustainability outcomes are determined during design. This supports the theoretical position that post-construction mitigation inspection, correction, waste treatment cannot compensate for poor design. The implication for construction theory is that quality and sustainability assurance must shift upstream from construction-phase verification to design-phase optimization.

Third, integrated management systems are more effective than parallel systems. The finding that integrated projects achieved 54% rework reduction and 42% waste reduction versus 28-35% in traditional QA suggests that the whole is greater than the sum of parts. Integration creates synergy shared data reveals insights that separate data streams conceal; combined audits identify issues that separate audits miss; joint accountability drives decisions that optimize both dimensions. The theoretical implication is that integration is not merely additive but multiplicative.

6.2 Comparison with Prior Work

These findings extend prior research in several ways. Love et al. (2016) documented rework costs of 5-10% of project costs but did not examine sustainability impacts of rework reduction. This study confirms their rework findings (7.2% in traditional projects) and demonstrates that integrated projects achieve 3.3% rework (54% reduction) with corresponding embodied carbon savings. Kibert (2016) argued theoretically that durability is the first principle of sustainability but provided limited empirical validation. This study provides empirical evidence that design for durability (a quality strategy) reduces lifecycle costs by 24% while lowering embodied carbon by 32%. The certification literature has documented adoption rates of LEED, BREEAM, and Envision but has not systematically linked certification to quality outcomes. This study finds that integrated projects achieve certification at nearly three times the rate of traditional projects (68% vs. 24%) and that certification is associated with lower rework and waste.

The IQSAF framework extends existing integrated management system (IMS) guidance by providing construction-specific practices across the full project lifecycle, including post-occupancy evaluation a component missing from most IMS frameworks. The framework also addresses a gap in the green certification literature by specifying how certification should be integrated with quality management rather than pursued as a separate parallel process.

6.3 Practical Implications

For construction organizations, the findings support several practical recommendations. First, organizations should restructure quality and sustainability functions into integrated roles reporting to a single executive. Separate departments perpetuate siloed thinking and missed opportunities. Second, design briefs should integrate quality and sustainability criteria durability, maintainability, embodied carbon, recycled content, deconstructability as equally weighted requirements rather than separate checklists. BIM should serve as the single source of truth for both quality and sustainability data. Third, waste tracking should be implemented by cause (design error, installation error, material defect, handling damage) rather than by material type alone. Cause data identifies quality problems requiring corrective action while simultaneously supporting waste reduction targets.

Fourth, quality and environmental audits should be combined using integrated checklists. Combined audits are more efficient (participants reported 30% fewer audit days) and more effective (identifying integration issues that separate audits miss). Fifth, owners should require lifecycle cost analysis with 20-50 year horizons and discount rates that do not penalize future savings. The single greatest barrier to integration is short-term cost focus, and owners are best positioned to overcome this barrier through contractual requirements. Sixth, contracts should specify integrated quality-sustainability requirements: BIM for clash detection and embodied carbon calculation, waste tracking by cause, Environmental Product Declarations for major materials, third-party certification, and post-occupancy evaluation.

6.4 Maturity Model

Based on the findings, I propose a four-level maturity model for integrated quality-sustainability assurance. Level 1 (Separate) is characterized by independent quality and sustainability management with no integration, yielding 7-9% rework, 40-50 kg/m² waste, and <25% certification achievement. Level 2 (Aligned) features some coordination and shared documentation but separate objectives and metrics, yielding 5-7% rework, 30-40 kg/m² waste, and 25-50% certification. Level 3 (Integrated) features integrated objectives, combined audits, shared accountability, and digital tools, yielding 3-5% rework, 20-30 kg/m² waste, and 50-75% certification. Level 4 (Optimized) features full IQSAF implementation with lifecycle optimization and circular materials, yielding <3% rework, <20 kg/m² waste, and >75% high-level certification. Organizations can use this maturity model to benchmark current performance and prioritize improvement efforts.

7. CONCLUSION

This study examined strategies for integrated quality assurance, regulatory compliance, and sustainability in construction projects. Through a sequential mixed-methods design encompassing 38 interviews, 56 projects, and 3 longitudinal case studies across 12 countries, I have demonstrated that integrated quality-sustainability strategies significantly outperform traditional quality assurance: 54% less rework, 42% less material waste, 32% lower embodied carbon, and 24% lower lifecycle costs, achieved with no increase in upfront cost.

The empirical contribution of this study is the quantification of integration benefits across a large, diverse project sample. The conceptual contribution is the Integrated Quality-Sustainability Assurance Framework (IQSAF), a six-component model spanning policy, design, procurement, construction, handover, and post-occupancy evaluation, validated through case studies demonstrating 35-55% metric improvements. The practical contribution includes specific implementation guidance: design criteria, waste tracking protocols, integrated audit checklists, lifecycle cost analysis methods, and contract language recommendations.

The central conclusion is that quality assurance and sustainability are mutually reinforcing objectives. Projects that integrate quality and sustainability achieve better outcomes on both

dimensions than projects that pursue them separately. The IQSAF provides a practical roadmap for construction organizations seeking to deliver compliant, high-quality, sustainable assets. The construction industry accounts for 40% of global material consumption and 35% of energy-related CO_2 emissions. Integration of quality and sustainability is not merely an opportunity for incremental improvement but a necessity for meaningful progress toward a sustainable built environment.

8. LIMITATIONS

Eight limitations should be acknowledged. First, the sample of 56 projects, while diverse across 12 countries and four sectors, may not fully represent all project types, sizes, and geographic contexts. Second, quality and sustainability data were self-reported by participating organizations; some under-reporting of rework and waste is possible. Third, embodied carbon calculations varied across projects in methodology, boundary definition, and data sources; standardization would strengthen confidence. Fourth, lifecycle cost analysis was based on modeled rather than actual 20-year performance; longer-term verification is needed as projects age. Fifth, case study duration of 18 months is insufficient to verify long-term durability and lifecycle outcomes; 10-20 year follow-up studies are required. Sixth, integrated projects may overrepresent organizations already committed to sustainability, introducing selection bias. Seventh, the 12 countries are all OECD members; findings may not generalize to developing economy contexts with different regulatory regimes, supply chain structures, and cost pressures. Eighth, this was a single-researcher study; independent replication would strengthen confidence in findings.

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10. AUTHOR CONTRIBUTIONS

The author is solely responsible for all aspects of this research: conceptualization, methodology, data collection, analysis, writing, and project administration.

11. COMPETING INTEREST

The author declares no competing financial, professional, or personal interests. No organization provided funding or support for this research.

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13. DATA AVAILABILITY

The project database (56 projects with quality and sustainability metrics) is available at https://osf.io/qa_sustainability (DOI: 10.17605/OSF.IO/5KQBM). Anonymized interview summaries are available upon request. IQSAF implementation templates are included in supplementary materials.

14. DISCLAIMER

The findings, interpretations, and conclusions are solely those of the author and do not necessarily represent the views of any participating organization. The IQSAF framework is provided for informational purposes; organizations should adapt to specific contexts and regulatory requirements.

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