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Bridging Material Innovation And Procurement For Circular Construction: A Lifecycle-Oriented Approach practice

Dr. Arman Patel

Department of Civil and Environmental Engineering, University of Toronto, Canada

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Abstract: Background: The construction sector is a principal consumer of natural resources and a major contributor to greenhouse gas emissions, waste generation, and environmental degradation. Transitioning from linear to circular paradigms in construction requires integration of material innovation, procurement reform, stakeholder collaboration, and lifecycle thinking. The literature contains numerous domain-specific investigations—ranging from the viability of using wastewater in concrete production to the mechanical performance of wood-plastic composites—yet there is fragmentation across technical, managerial, and policy dimensions. This study synthesizes diverse evidence to present a comprehensive, theoretically grounded framework for circular construction that connects recycled-material technologies with procurement strategies and lifecycle environmental accounting.

Objectives: This article aims to (1) consolidate empirical findings on recycled and alternative construction materials; (2) analyze procurement and delivery models that enable circular outcomes; (3) propose an integrated methodological approach for assessing circularity across technical performance, environmental impact, and stakeholder dynamics; and (4) identify research gaps and propose a nuanced agenda for policy, practice, and scholarship.

Methods: Using the provided reference corpus as the evidentiary base, this work implements an analytical synthesis method grounded in cross-disciplinary theory building. Technical studies on recycled aggregates, wood-based alternatives, and plastic composites are synthesized with procurement and project-delivery literature to derive a systemic conceptual model. Evidence is interrogated via comparative thematic analysis and hypothetical scenario projections, emphasizing consistency with the original empirical findings while extrapolating theoretical implications.

Results: The synthesis reveals convergent findings: high-quality recycled aggregates and sands are reaching industrial readiness (Skocek et al., 2024; Ulewicz, 2021), wood-based materials present substantial carbon benefits when managed across long cycles (Nielsen-Roine & Meyboom, 2024; Gustavsson & Sathre, 2006), and plastic-derived composites can replace selected non-structural components with favorable environmental trade-offs (Ribeiro et al., 2023; Lamba et al., 2022). Procurement mechanisms and collaborative delivery models emerge as critical enabling conditions; misaligned procurement disincentivizes circular practices (Mitchell, 2015; Osipova & Eriksson, 2011; Ofori, 2007). Lifecycle analyses underscore the importance of demolition-phase emissions and embodied carbon from material choices (Egonzalez et al., 2022; Gustavsson & Sathre, 2011).

Conclusions: A multi-layered framework is proposed that links material selection criteria, quality-assurance pathways for recycled inputs, procurement reform, and lifecycle accounting. Policy levers, industry standards, and novel contractual forms are necessary to scale circular construction. Future research must prioritize long-term field trials, standardization of recycled material specifications, and integrative socio-technical studies that examine how stakeholder incentives shape circular outcomes.

Keywords: Circular economy, recycled materials, construction procurement, lifecycle assessment, recycled aggregates, wood-based construction.

Introduction: The global construction industry stands at the intersection of resource scarcity, urbanization pressures, and climate imperatives. Buildings and infrastructure consume vast quantities of raw materials and energy, while generating significant waste during construction, renovation, and demolition. A transition toward circular construction—characterized by reuse, recycling, remanufacture, and longer life cycles—has been widely advocated but remains challenging in practice (Osobajo et al., 2020; Ogunmakinde et al., 2021). The challenge is not only technical but organizational and institutional: materials that are recycled or derived from waste streams must meet technical specifications, procurement mechanisms must enable their adoption, and lifecycle accounting must capture the environmental benefits and trade-offs.

This article addresses three interconnected problems. First, the technical viability and performance of recycled and alternative materials in structural and non-structural applications are unevenly documented; while some recycled aggregates and engineered wood products show promise, their widespread adoption is limited by variability in quality and limited standardization (Skocek et al., 2024; Ulewicz, 2023). Second, procurement practices, risk allocation, and stakeholder influence strategies often impede circular solutions; traditional procurement may favor lowest-bid approaches that neglect lifecycle implications (Mitchell, 2015; Oyegoke et al., 2009). Third, lifecycle emissions and demolition-stage carbon costs are frequently underestimated or separated from material decisions, obscuring the environmental gains of circular approaches (Egonzalez et al., 2022; Gustavsson & Sathre, 2011).

The literature offers detailed, domain-specific studies. For instance, the use of domestic and industrial wastewaters in concrete production has been reviewed comprehensively, showing feasibility under controlled conditions while highlighting the need for robust testing and quality control (Sheikh Hassani et al., 2023). Recycled sand and aggregates are being engineered for industrial production with improved properties such as low water absorption (Skocek et al., 2024). Wood chips and sawdust in concrete have been experimentally evaluated for their mechanical and durability properties (Dias et al., 2022). Separately, systematic reviews evaluate wood-plastic composites made from post-consumer plastics for building components, charting both potential and limitations (Ribeiro et al., 2023). These studies provide a mosaic of technical knowledge but do not, in isolation, prescribe system-level pathways for adoption.

Procurement, governance, and behavioral elements in collaborative delivery models have been explored by management scholars (Moradi et al., 2022; Nguyen et al., 2019), emphasizing the importance of stakeholder strategies for project outcomes. Procurement reform is identified as a research agenda, particularly in developing countries where formal mechanisms may lag (Ofori, 2007). Studies also indicate that public procurement can be a powerful lever for circular economy implementation in construction (Plebankiewicz, 2022). Yet the connection between procurement mechanisms and the technical readiness of recycled materials remains underdeveloped in the literature.

This article seeks to bridge these divides. By synthesizing empirical results on recycled materials, exploring procurement and delivery models that can embed circularity, and applying lifecycle reasoning to quantify environmental trade-offs conceptually, the work develops a cohesive, publication-ready framework. The approach is deliberately synthetic and theoretical:

rather than presenting new experimental data, it integrates the provided references into a consolidated argument, highlighting the conditions under which circular construction can be technologically, economically, and institutionally viable.

Methodology

This study uses an integrative synthesis methodology that treats the provided references as primary evidence for building a system-level argument. The methodology has three interlocking components: systematic evidence mapping, comparative thematic analysis, and model construction through theoretical integration.

Systematic evidence mapping: Each reference was examined for its domain, methods, key findings, and limitations. Technical studies (e.g., on concrete, recycled aggregates, wood chips) were catalogued with attention to performance metrics such as compressive strength, water absorption, durability markers, and treatment/processing methods. Management and procurement literature were mapped for themes related to procurement options, risk management, stakeholder influence, and collaborative delivery behavior.

Comparative thematic analysis: Using the mapped evidence, recurring themes were identified. These themes included (a) material-quality variability and industrial readiness, (b) lifecycle and embodied carbon considerations, (c) procurement mechanisms as enablers or barriers, and (d) socio-technical integration challenges. The analysis sought to juxtapose technical feasibility with institutional feasibility, examining where empirical findings from material science align or conflict with procurement and organizational literature.

Model construction through theoretical integration: Based on the thematic analysis, a conceptual framework was developed that integrates technical criteria for recycled materials, procurement pathways, and lifecycle accounting. The framework is articulated through descriptive text and scenario-based reasoning. Hypothetical project scenarios were constructed to demonstrate how different procurement choices and material selections would interact to produce varying environmental and performance outcomes. While no new experimental data were generated, the scenarios rely on quantitative cues reported in the literature (e.g., reported embodied carbon ranges, material property differentials) and use descriptive extrapolation to retain transparency.

Rigor and validity: The synthesis prioritizes fidelity to the original references. All major claims and empirical generalizations are directly attributed to the referenced works in (Author, Year) format. Where theoretical extrapolation occurs, the text explicitly identifies inferential steps and presents counter-arguments to ensure balanced scholarly treatment.

Limitations of methodology: The approach is constrained by reliance on the supplied reference list; the absence of complementary sources may limit the breadth of empirical coverage. Theoretical extrapolations are presented as interpretative rather than definitive; the article therefore frames subsequent empirical testing as necessary to validate the proposed framework.

Results

The results section synthesizes the technical and managerial evidence into patterns, propositions, and scenario illustrations. It is organized into four thematic subsections: (1) technical viability of recycled and alternative materials, (2) lifecycle and environmental implications, (3) procurement and delivery models as enablers, and (4) integration challenges and readiness for industrial adoption.

Technical viability of recycled and alternative materials

Recycled aggregates and sands: Recent experimental and field-oriented studies demonstrate that recycled aggregates and sands can reach performance levels appropriate for structural concrete under improved processing regimes. Skocek et al. (2024) document industrial production strategies that yield high-quality recycled materials with low water absorption—an important property for concrete workability and durability. Ulewicz (2021, 2023) further outlines how recycled materials, when carefully characterized and processed, can be used in concrete and other composites. The technical viability is contingent on controlled processing steps: shredding, sieving, contaminant removal, and, in some cases, surface treatment to reduce porosity and water absorption. Where these steps are systematically applied, recycled aggregates approach the tensile and compressive characteristics necessary for structural applications (Skocek et al., 2024; Ulewicz, 2021).

Concrete with wastewater: The literature review by Sheikh Hassani et al. (2023) synthesizes studies where domestic and industrial wastewater were integrated into concrete production, replacing potable water in mixing. The reported outcomes indicate potential for maintaining desirable hydration and strength profiles, provided the wastewater is subject to pre-treatment that removes deleterious organics and controls salinity and ionic composition. The review underscores the need for standardized quality thresholds and testing regimes to ensure consistent outcomes across production batches (Sheikh Hassani et al., 2023).

Wood-based inclusions and substitutes: Wood chips and sawdust, often regarded as low-value residues, have been studied as partial replacements in concrete or as constituent materials in composite panels. Dias et al. (2022) conducted experimental analyses that reveal nuanced results: wood inclusions can reduce density and embodied carbon while adversely affecting compressive strength and durability if used at high replacement ratios. The mechanical and durability behavior depends on particle size, treatment for water affinity, and the interaction between organic particles and cementitious matrices. The implications are that wood-derived materials are promising for non-load-bearing panels, thermal insulation components, and instances where reduced weight and improved thermal performance are prioritized (Dias et al., 2022; Nielsen-Roine & Meyboom, 2024).

Plastic-based composites and building components: Post-consumer plastics have been systematically reviewed for use in wood-plastic composites and building components (Ribeiro et al., 2023; Lamba et al., 2022). The consensus is that plastics—when processed with fillers, compatibilizers, and appropriate manufacturing techniques—can deliver durable, decay-resistant, and lightweight components suitable for cladding, decking, and non-structural elements. Performance trade-offs include thermal sensitivity, creep under sustained loading, and issues with fire performance that must be engineered through additives and design choices (Ribeiro et al., 2023).

Performance trade-offs and quality control: Across material classes, a common theme is the trade-off between environmental benefits and technical performance. Recycled materials frequently show enhanced environmental profiles but require tighter quality-control systems to achieve mechanical parity with virgin materials. The literature stresses the importance of standardization, robust testing, and the establishment of acceptance criteria to mitigate risk and variability (Skocek et al., 2024; Ulewicz, 2023).

Lifecycle and environmental implications

Embodied carbon and demolition emissions: Lifecycle analyses and case-specific studies illustrate that material choices and end-of-life handling significantly affect a building's carbon profile. Egonzalez et al. (2022) estimate the carbon cost associated with concrete building demolitions in the aftermath of seismic events, demonstrating that demolition and disposal can contribute materially to lifecycle emissions. Gustavsson and Sathre (2006, 2011) provide in-depth analyses showing that substituting wood for concrete in specific applications can reduce lifecycle emissions, but such benefits hinge on forest management, substitution rates, and the fate of harvested wood (Gustavsson & Sathre, 2006; Gustavsson & Sathre, 2011). The central implication is that circular strategies should be evaluated across a building's entire lifecycle—construction, use, renovation, and demolition—rather than isolated material substitution.

Wastewater reuse effects: The use of wastewater in concrete may lead to reduced potable water consumption, which is an important environmental benefit. However, the lifecycle impact must account for treatment energy, potential additives to address contaminants, and any long-term durability implications that affect service life. Sheikh Hassani et al. (2023) highlight that water reuse can be environmentally beneficial if technical performance is ensured.

Material longevity and functional obsolescence: Durability is a crucial pathway through which circularity yields environmental benefits. Materials that fail prematurely or require frequent replacement can negate initial embodied-carbon savings. Dias et al. (2022) and Ribeiro et al. (2023) emphasize that the durability of wood-inclusive and plastic composites determines whether their reduced embodied carbon actually translates into lifecycle advantages.

Procurement and delivery models as enablers

Procurement influence on circularity: Procurement approaches determine incentive structures, risk allocation, and which actors bear responsibilities for material quality and lifecycle outcomes. Traditional procurement—particularly lowest-bid models—often discourages the adoption of recycled materials due to perceived risk and variability (Mitchell, 2015; Oyegoke et al., 2009). Conversely, procurement practices that incorporate lifecycle criteria, performance-based specifications, and collaborative contracting can create pathways for circular materials (Plebankiewicz, 2022; Osobajo et al., 2020).

Collaborative delivery and stakeholder behavior: Behavioral and collaborative elements of project delivery models are critical. Moradi et al. (2022) and Nguyen et al. (2019) discuss how stakeholder influence strategies and collaborative behaviors shape project outcomes. In circular contexts, early involvement of material suppliers, contractors with experience in recycled-material handling, and designers who can integrate alternative materials into functional designs is essential to manage risk and ensure constructability.

Risk management and procurement options: Osipova and Eriksson (2011) analyze how procurement choices influence risk distribution. Contracts that transfer excessive technical risk to contractors without commensurate incentives or support for material innovation will likely suppress circular adoption. Balanced contracts, shared savings models, and procurement frameworks that include innovation allowances can reconcile the need for performance assurance with the promotion of circular materials.

Public procurement as policy lever: Plebankiewicz (2022) documents how public procurement can be intentionally used to implement circularity in construction. Governments and public agencies can stipulate recycled-content requirements, prioritize lifecycle outcomes, and fund pilot projects that de-risk novel materials for private sector uptake.

Integration challenges and industrial readiness

Standardization and certification: A persistent barrier to industrial adoption is the lack of widely accepted standards for recycled materials, particularly those derived from heterogeneous waste streams. Skocek et al. (2024) and Ulewicz (2023) stress that standardization around processing methods, testing protocols, and acceptance criteria is essential for scaling recycled aggregates and sands to industrial production.

Supply chain logistics and material traceability: Circular materials require robust supply chains that can deliver consistent quality. The literature identifies logistical bottlenecks—collection, sorting, pre-processing facilities—that must be addressed through investment and policy incentives (Lamba et al., 2022; Ren, 2024). Traceability systems that certify material provenance and treatment history increase buyer confidence and enable lifecycle accounting.

Economic feasibility: Economic analyses suggest that recycled materials can be cost-competitive when externalities are internalized or when logistics and scale effects are optimized. Hasan (2021) discusses the feasibility of recycling concrete construction waste from environmental and economic perspectives, indicating that economic viability is sensitive to local disposal costs, regulatory frameworks, and the market for recycled materials.

Behavioral inertia and institutional barriers: Even with technical readiness and favorable economics, institutional inertia and risk-averse culture can impede adoption. The procurement literature documents how entrenched practices, limited technical capacity, and fragmented project delivery create path dependencies that resist change (Mitchell, 2015; Ofori, 2007).

Scenario illustrations

To concretize the interactions among material choices, procurement models, and lifecycle outcomes, consider two hypothetical municipal building projects that differ only in procurement and material selection approaches.

Scenario A: Lowest-bid procurement, conventional materials. The municipality issues a contract that emphasizes first-cost minimization with minimal lifecycle criteria. The winning contractor uses virgin aggregates and standard concrete mixes with potable water. The initial capital cost is low, but the embodied carbon is relatively high, and demolition-stage waste requires transport to landfill. If the building requires substantial renovation within decades, cumulative emissions increase. This scenario replicates many real-world projects where short-term cost criteria dominate (Mitchell, 2015; Egonzalez et al., 2022).

Scenario B: Performance-based procurement with circular material incentives. The municipality issues a contract that rewards lifecycle performance, includes minimum recycled content, and allows for contractor innovation with shared savings. The contractor sources industrially produced recycled sand and aggregates processed to low water absorption specifications (Skocek et al., 2024) and integrates wood-composite interior panels made from certified wood chips and sawdust for non-structural uses (Dias et al., 2022). Wastewater reuse for mixing is implemented following pre-treatment protocols (Sheikh Hassani et al., 2023). Lifecycle modeling indicates reduced embodied carbon and lower demolition emissions if deconstruction is planned to facilitate material recovery (Egonzalez et al., 2022; Gustavsson & Sathre, 2011). Upfront costs may be slightly higher, but risk sharing and performance incentives align contractor behavior to long-term sustainability goals (Plebankiewicz, 2022; Osipova & Eriksson, 2011).

These scenarios demonstrate how procurement design mediates the environmental performance of otherwise similar projects. Scenario B requires institutional capacity, standardization, and stakeholder alignment but yields better lifecycle outcomes when these enabling conditions are met.

Discussion

This section interprets the synthesized findings, explores theoretical implications, identifies practical barriers, and outlines a forward-looking research and policy agenda. The discussion emphasizes the intertwined technical, managerial, and lifecycle dimensions of circular construction.

Technical implications and research directions

Material processing and performance pathways: The technical literature highlights critical processing steps that transform low-quality waste materials into high-performing recycled aggregates and sands. The insights from Skocek et al. (2024) about reducing water absorption through industrial processing are particularly salient. Research should focus on quantifying processing-cost-to-performance curves—how incremental investment in processing reduces variability and increases mechanical reliability. Experimental studies should isolate which processing techniques (e.g., thermal, chemical, mechanical attrition) most cost-effectively improve properties.

Durability and long-term performance: Several references indicate uncertainty about the long-term durability of wood-inclusion concretes and plastic composites under real-world exposure conditions (Dias et al., 2022; Ribeiro et al., 2023). There is a need for longitudinal field trials that track materials across seasons, loading regimes, and maintenance practices. Such trials would provide the empirical basis for service-life predictions, which are foundational to lifecycle accounting.

Material compatibility and composite behavior: The insertion of organic materials (wood chips, sawdust) or plastic composites into cementitious matrices introduces complex interfacial chemistry issues. Research into surface treatments, coupling agents, and hybrid binder systems (e.g., geopolymer binders) could improve interfacial adhesion and reduce premature degradation. These avenues align with broader materials science efforts to create hybrid composites tailored for circular construction.

Standardization and test development: The creation of universally accepted test protocols for recycled aggregates, wastewater use, and composite panels is essential. Standardization would enable producers to certify materials, reduce transaction costs for buyers, and facilitate regulatory acceptance. Standards organizations and industry consortia should prioritize test methods that are sensitive to the unique failure modes and variability of recycled materials.

Managerial and procurement implications

Procurement reform as structural enabler: The procurement literature within the reference list emphasizes that procurement choices materially affect the uptake of circular materials. Moving from lowest-bid paradigms to performance-based contracting introduces incentives for lifecycle thinking (Mitchell, 2015; Plebankiewicz, 2022). Contracts that include lifecycle targets, bonus structures for material recovery rates, and innovation allowances can catalyze investment in processing facilities and quality assurance.

Risk allocation and collaborative models: Osipova and Eriksson (2011) and Moradi et al. (2022) illustrate how procurement options influence risk management. For recycled-material adoption, risk-sharing models—where designers, contractors, and material suppliers co-own performance outcomes—are preferable. Collaborative delivery models such as integrated project delivery (IPD) or alliances can operationalize risk-sharing and enable early-stage supplier engagement, thereby reducing uncertainty.

Capacity building and knowledge transfer: A key practical barrier is limited technical capacity among contracting authorities and small contractors to evaluate and manage recycled materials. Training programs, demonstration projects, and knowledge-sharing platforms can build confidence and technical competence. Public agencies can play a catalytic role by sponsoring pilot projects and disseminating lessons learned.

Public policy levers and market development: Public procurement represents an underutilized lever for market development (Plebankiewicz, 2022). By setting recycled-content thresholds, offering tax incentives, or internalizing disposal costs through landfill taxes, policymakers can change relative economics in favor of circular materials. Additionally, regional planning that supports the location of pre-processing facilities near demolition sites can reduce logistics costs and encourage material recirculation (Ren, 2024).

Lifecycle accounting and systems perspectives

Holistic lifecycle assessment: The findings underscore the necessity to embed lifecycle accounting into material and procurement decisions. Embodied carbon, operational emissions, and demolition-stage impacts must be evaluated collectively. Egonzalez et al. (2022) demonstrate the magnitude of demolition-related emissions in post-disaster contexts, emphasizing that end-of-life considerations can dominate lifecycle profiles.

Functional unit and system boundaries: Lifecycle assessments must carefully define the functional unit and system boundaries. For example, substituting wood for concrete in a wall system requires assessing functional performance (strength, fire resistance, durability), service life, and maintenance needs. Gustavsson and Sathre (2006, 2011) demonstrate that substitution benefits are contingent on system-level equivalence and forest-regeneration dynamics.

Deconstruction and material recapture: Circular outcomes are enhanced when buildings are designed for deconstruction, enabling material recapture with lower contamination and processing costs. Procurement specifications can require deconstruction planning and set targets for recovered-material reuse. Such measures require collaboration between designers, contractors, and waste processors.

Limitations and counter-arguments

Uncertainty in performance and scale: Despite promising laboratory and pilot results, scaling recycled-material production to supply construction markets at scale introduces uncertainty. Variability in waste streams, collection inefficiencies, and capital requirements for processing facilities are significant barriers. Critics might argue that reliance on recycled materials could create supply bottlenecks or mediate performance compromises; these concerns reinforce the need for diversified strategies that include material substitution, efficiency improvements, and design for longevity.

Economic competitiveness without policy support: Recycled materials may require policy support to be cost-competitive in markets where disposal of virgin materials and externalities are not priced. Economic feasibility assessments must consider context-specific variables such as local disposal costs, transportation distances, and regulatory frameworks (Hasan, 2021).

Potential trade-offs in environmental outcomes: Circular materials can have unintended environmental trade-offs—e.g., energy-intensive processing of contaminated aggregates or additives used to enhance plastic composite fire performance may raise lifecycle impacts. Lifecycle assessments must be comprehensive to reveal such trade-offs, and procurement frameworks must avoid narrow metrics that could produce perverse incentives.

Future research agenda

Longitudinal performance studies: Multi-year, real-world monitoring of buildings constructed with significant recycled-content materials is essential to validate service-life projections and lifecycle claims.

Integration of digital traceability: Research should explore digital tools—blockchain, material passports—to enhance traceability and assurance of recycled material provenance and treatment history.

Hybrid procurement experimentation: Field experiments that test procurement models (e.g., performance-based contracts with shared savings) in varied contexts would produce practical insights into incentive alignment and risk distribution.

Cross-disciplinary socio-technical studies: Studies that blend materials science with organizational behavior and policy analysis can illuminate how technical readiness and institutional capability co-evolve.

Economic modeling with externalities: Robust economic models that internalize environmental externalities, consider economies of scale in processing, and capture regional logistics dynamics would inform policy design.

Conclusion

This article synthesizes a multidisciplinary corpus of literature to articulate a systemic framework for circular construction that integrates recycled-material technologies, procurement reform, and lifecycle accounting. Technical advances in recycled aggregates, engineered wood products, and plastic composites provide a foundation for substitution and reuse; however, industrial adoption hinges on standards, processing infrastructure, and robust quality assurance. Procurement mechanisms—public and private—can either entrench linear outcomes or catalyze circular practices depending on how contracts allocate risk, reward innovation, and incorporate lifecycle metrics. Lifecycle analyses reveal the paramount importance of end-of-life considerations and demolition-stage emissions, underscoring the need for design for deconstruction, material traceability, and policy levers that correct market failures.

The transition to circular construction is feasible but requires coordinated action across technical, managerial, and political domains. Standardization of recycled-material tests, piloting of collaborative procurement models, investment in pre-processing infrastructure, and comprehensive lifecycle accounting are immediate priorities. Future research should move beyond isolated technical studies to integrated, longitudinal, and cross-disciplinary investigations that can validate lifecycle benefits, provide standardized pathways for certification, and map the institutional reforms necessary to scale circularity. Only through such an integrated approach can the construction sector reconcile the imperatives of resource conservation, climate mitigation, and enduring built-environment performance.

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