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Original Research Article

Strategic Financing of Energy Efficiency Solutions in Saudi Arabia's Power Generation Sector: An Investment Framework for Vision 2030

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Abstract: Saudi Arabia's construction pipeline creates a practical resource-management challenge: project teams must reduce dependence on virgin aggregates and clinker-intensive products while controlling the quality, cost, durability and traceability risks associated with secondary materials. This review therefore moves beyond a general catalogue of recycled construction materials and develops a project-level implementation framework for Saudi building and infrastructure delivery. Thirty publications from 2020–2025 were synthesized around five decision stages: source identification, material qualification, application selection, procurement and approval, and site production control. Evidence on recycled concrete aggregate (RCA), reclaimed components, waste glass, plastics, steel slag, supplementary cementitious materials, geopolymer systems and recycled water is translated into practical acceptance gates for design, materials engineering, procurement, QA/QC and construction teams. The review shows that recycled content alone is a weak decision metric. For Saudi projects, the more defensible approach is to match the secondary material to a defined application and exposure class, verify source quality and contamination limits, validate trial mixtures or product performance, control moisture and batch variability, and document environmental and economic benefit at the functional-unit level. A role-based implementation matrix, stage-gate approval protocol and project KPI set are proposed to support real project execution under Vision 2030. The resulting framework is intended to help project teams convert circular-economy objectives into auditable material approvals, procurement decisions, inspection points and measurable resource-efficiency outcomes rather than treating recycling as a stand-alone sustainability claim.

Keywords: Saudi Vision 2030, Construction Material Approval, Recycled Concrete Aggregate, Construction and Demolition Waste, QA/QC, Circular Procurement, Material Traceability, Resource Efficiency, Project Delivery.

1. INTRODUCTION

The construction sector is highly material-intensive, as buildings and infrastructure require substantial quantities of aggregates, cement, steel, glass, polymers, gypsum, water and finishing products. In a linear sourcing model, extraction and manufacturing are followed by use, demolition and disposal. This sequence creates three interrelated pressures: depletion of natural resources, greenhouse gas emissions and pollution from processing and transport, and increasing construction and demolition waste (CDW). Recent research increasingly treats CDW not only as an end-of-life burden but also as an urban material stock that can supply future construction activities [2–6]. This perspective is especially relevant in rapidly developing economies, where infrastructure programs simultaneously increase raw-material demand and the need for waste-management capacity.

Saudi Arabia provides a significant context for promoting resource-efficient construction. Vision 2030 has accelerated investments in housing, transport, tourism, industry, and urban transformation, while environmental policy increasingly prioritizes waste diversion, resource productivity, and circular-economy practices. A life-cycle assessment of CDW management in Riyadh demonstrated that increasing recycling rates beyond current baselines is able to mitigate impacts associated with landfilling and virgin material production [7]. Another study in the Saudi building sector found that although actors are aware of circular-economy concepts, regulatory, market, and organizational barriers hinder feasible implementation [8]. These outcomes indicate that the technical feasibility of using waste-derived materials is only one aspect of the wider challenge. Achieving resource-efficient construction also requires effective collection systems, assurance of material quality, appropriate procurement policies, risk allocation, logistics, standards, traceability, and robust life-cycle evidence.

Recycled concrete aggregate (RCA) is the most mature pathway because demolished concrete can be crushed, screened and graded to replace natural aggregate in road layers, blocks, non-structural concrete and, under regulated conditions, structural concrete [2-10]. Yet RCA is not equivalent to virgin stone. Residual mortar creates higher porosity and water absorption, while multiple interfacial transition zones can influence stiffness, shrinkage, chloride ingress and strength [2-11]. Recent studies have consequently moved from simple replacement-ratio experiments toward quality classification, surface treatment, supplementary cementitious materials, nano-modification and performance-based mixture design [12–18]. This evolution is important for Saudi Arabia because a resource-efficient strategy should not force high recycled content into unsuitable applications. It ought to match material quality to performance requirements.

Resource efficiency encompasses more than concrete aggregate. Waste glass can serve as aggregate or as a finely ground supplementary material; recycled plastics may be selectively incorporated as fibers or lightweight aggregate; steel slag can replace mineral aggregate in suitable applications; and fly ash, slag and other industrial by-products can reduce clinker demand. Alkali-activated or geopolymer binders can also utilize waste-derived precursors [1–22]. Alhazmi *et al.*, [1], are particularly relevant because they combined recycled aggregate geopolymer concrete with industrial effluent and assessed mechanical, durability and cost performance, thereby illustrating how multiple secondary streams can be integrated within one material system. Such integration, however, must be evaluated for contaminant risk, local availability, durability, transport and end-of-life implications rather than assumed to be sustainable merely because waste is consumed.

A review aligned with Saudi Vision 2030 must integrate material science with the decisions made during design, procurement, construction and quality control. Global reviews frequently explain recycled aggregate properties, while Saudi-focused studies often emphasize waste systems or stakeholder barriers. What is less developed is the project-facing question: what evidence should a materials or project team request before approving a secondary material, where should it be used, which risks should trigger rejection or restricted use, and how should the decision be documented so that procurement, QA/QC and site teams act consistently? This paper addresses that gap by converting evidence published between 2020 and 2025 into a stage-gate framework for source assessment, material characterization, trial validation, application assignment, procurement control and field traceability. The contribution is therefore not another inventory of 'green materials'; it is a decision-oriented synthesis designed for implementation in Saudi construction workflows.

1.1 Aim and Objectives

The aim of this review is to translate recent research on recycling and reuse into an operational material-management framework for Saudi construction projects under Vision 2030. Six objectives guide the study: (1) identify the secondary material streams with the strongest potential for buildings, roads and infrastructure; (2) define the source, quality and durability information required before those materials are accepted; (3) map recycled-material decisions to practical project stages including design, material submittal, procurement, trial production, inspection and installation; (4) clarify the responsibilities of design, materials, QA/QC, procurement, construction and sustainability functions at each decision gate; (5) establish project-level KPIs for resource savings, traceability, cost and performance; and (6) develop a Saudi-focused adoption pathway that gives priority to fit-for-purpose use rather than maximum recycled-content percentages. Unlike a conventional narrative review, the intended output is a practical control framework that can be applied to material selection and approval on live projects.

2. REVIEW METHODOLOGY

A structured integrative review method was selected because the research question spans experimental material studies, review articles, life-cycle assessments, and Saudi implementation research. The search window was restricted to 2020–2025 to meet the study requirement and to capture current processing, durability, circularity and environmental-assessment approaches. Search terms were combined around four concept groups: “construction and demolition waste” or “recycled aggregate”; “concrete,” “construction material,” “geopolymer,” “glass,” “plastic,” or “slag”; “life cycle,” “resource efficiency,” “circular economy,” “durability,” or “reuse”; and “Saudi Arabia,” “Riyadh,” or “Vision 2030” where regional evidence was required.

Sources were screened in three stages. First, titles and abstracts were assessed for direct relevance to material recycling, reuse, or circular construction. Second, studies were retained when they reported at least one of four evidence types: material-property data, durability or microstructural interpretation, environmental or economic assessment, or implementation barriers and enablers. Third, we preferred peer-reviewed journal articles with clear bibliographic metadata and traceable digital object markers. The final evidence set excluded pre-2020 publications, duplicate records, studies focused only on municipal waste without construction-material application, and papers lacking sufficient methodological detail.

The final synthesis included 30 publications [1–30]. Statistical pooling was not appropriate because material sources, replacement ratios, exposure conditions, treatment methods, functional units and test procedures were heterogeneous. Instead, each source was coded against an applied decision matrix: material source and processing route; critical input properties; suitable application tier; mechanical and durability evidence; environmental and cost implications; implementation barriers; project function responsible for the decision; and the evidence needed to pass an approval gate. Cross-study conclusions were accepted only when supported by multiple publications or by a directly relevant Saudi case. Conflicting results were retained and interpreted through differences in source quality, residual mortar, moisture state, treatment intensity, binder composition, transport assumptions and exposure conditions. This coding structure intentionally links literature findings to project decisions rather than summarizing studies material-by-material only.

The method has two deliberate boundaries. It does not claim to calculate a national material-flow inventory for Saudi Arabia because consistent project-level quantities are not available in the reviewed literature. It also does not prescribe one recycled-content percentage for all applications because performance depends on feedstock quality, exposure class, processing and product function. The proposed project controls are therefore presented as evidence-informed decision rules, not as substitutes for project specifications or statutory requirements. This distinction is important: the review uses published evidence to define where verification is needed, while the final acceptance value for a specific project must come from the governing specification, approved mix design, supplier data and project testing regime.

3. Saudi Arabia Context: Resource Efficiency and Vision 2030

Saudi Arabia’s resource-efficiency opportunity stems from the scale and geography of its construction program. Large urban developments require enormous quantities of particulate materials and cement-based products, while demolition, excavation and redevelopment create secondary mineral streams that are expensive to transport and landfill. Because aggregates are heavy and relatively low in unit value, local processing can be environmentally preferable when recycling facilities are close to generation and use points. Haider *et al.*, [7], showed this principle in Riyadh by comparing CDW management scenarios using life-cycle assessment. Their results supported higher recovery because recycling avoids part of the burden associated with landfilling and primary material supply. The study also shows why local conditions matter: environmental outcomes depend on actual collection, sorting, processing, residual fines, and transport distances rather than global-average assumptions.

Circularity in Saudi construction is therefore both a materials problem and an institutional problem. AlJaber *et al.*, [8], found that building-sector stakeholders recognized circular-economy concepts, yet barriers including limited regulation, market readiness, knowledge, and coordination constrained implementation. More recent Saudi studies on mega-project waste and circular-economy practices reinforce the need to prevent waste at source, improve segregation and create reliable recovery markets [23, 24]. If mixed demolition debris arrives at a recycler with soil, gypsum, wood, plastics and contaminants, the resulting aggregate quality becomes variable and higher-value applications become difficult. Source separation and selective demolition should consequently be considered upstream material-engineering measures, not simply waste-management activities.

Vision 2030 alignment is strongest when recycling creates value that can be demonstrated at work-package level. A project team should be able to show which virgin material was avoided, where the secondary material originated, how far it travelled, how it was processed, which tests qualified it, where it was installed and whether its performance was equivalent to the specified function. This creates a stronger link between circular-economy ambition and routine project controls. It also exposes trade-offs early: poorly processed RCA may demand additional cement or corrective admixture; a distant recycling plant may remove the transport advantage; and uncontrolled mixed demolition waste may be unsuitable for higher-value concrete applications. The Saudi opportunity is therefore not simply 'more recycling', but better allocation of secondary materials to the right work packages, supported by quality evidence, short logistics loops and traceable procurement records [7-24].

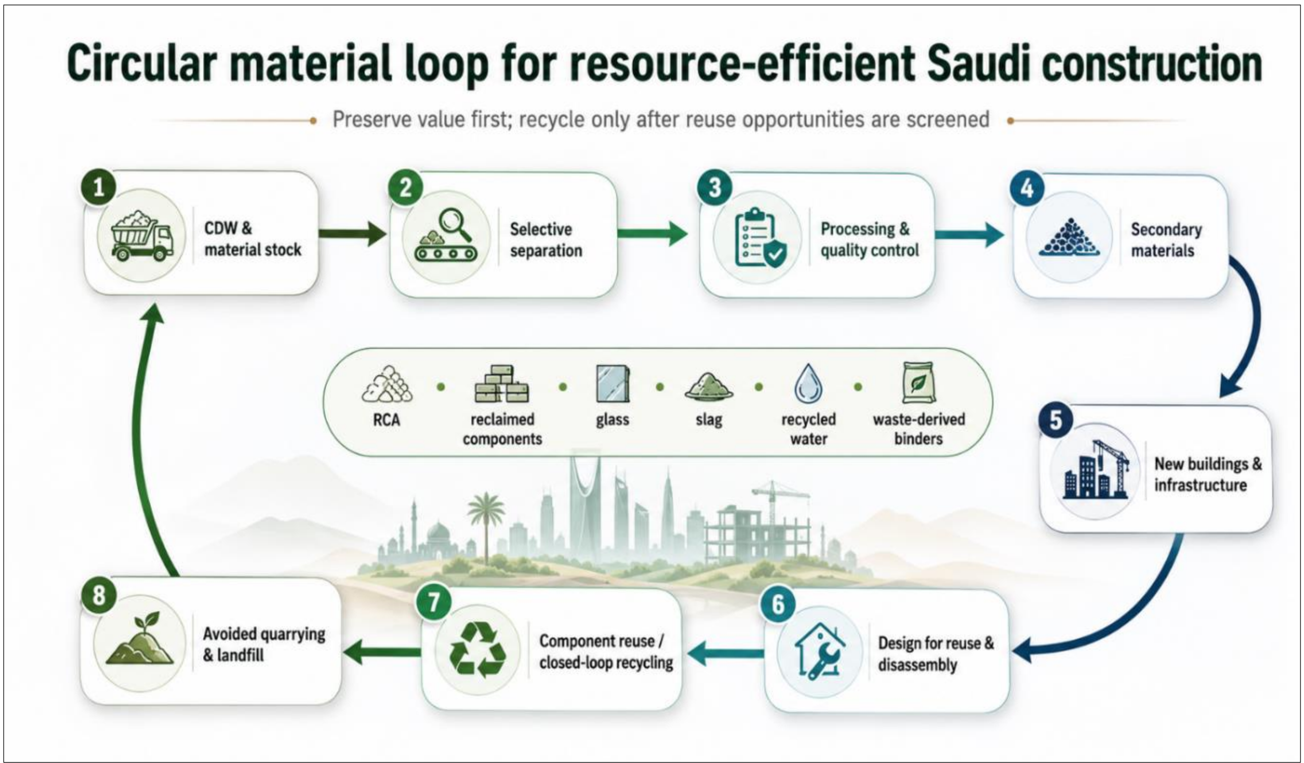

Figure 1: Circular material loop proposed for resource-saving Saudi construction

4. Recycled and Reused Material Pathways

Recycled concrete aggregate is the central mineral pathway because concrete forms a large share of CDW and can be processed with mature crushing and screening equipment. Wang *et al.*, [2], and Salgado and Silva [9], identify attached mortar as the defining difference between RCA and natural aggregate. It increases water absorption, lowers density, and creates a more heterogeneous surface. These characteristics affect mixture water demand and the new interfacial transition zone, which explains why uncontrolled high replacement can reduce compressive strength or elastic modulus. Abera [10], similarly concludes that performance varies considerably with CDW source and aggregate quality. For Saudi practice, this evidence supports mandatory characterization of density, absorption, grading, contamination, abrasion resistance, and parent-material history before assigning RCA to a concrete class.

The evidence also shows that RCA should not be treated as a single product. Quality can be improved by removing weak adhered mortar, optimizing comminution stages, pre-soaking, mechanical abrasion, acid treatment, carbonation or coating. Peiris *et al.*, [18], review treatment methods and show that improvement must be balanced against cost, energy, and chemical use. A treatment that produces stronger aggregate but consumes ample energy may not improve system-level sustainability. A tiered market is therefore preferable: lightly processed mixed recycled aggregate can serve road subbase or fill; controlled concrete-derived RCA can serve blocks and pavements; and certified high-quality RCA can enter structural concrete where performance requirements are met.

Binder engineering is equally important. Wang *et al.,* [12], report that supplementary cementitious materials such as fly ash, ground granulated blast-furnace slag, silica fume and metakaolin can refine the pore system of RAC and compensate for weaknesses associated with porous RCA. Gao *et al*., [13], and Lu *et al*., [14], show that the interfacial transition zone governs much of the performance, while nanoscale modification can densify this region. Sun *et al.,* [15], further demonstrate combined modification using nano-silica and fibers. These approaches shift recycled concrete design away from a simple substitution concept toward engineered multi-phase systems. In Saudi Arabia, this is valuable because durability under hot, dry, saline, and coastal exposures may matter more than achieving a nominal recycled-content target.

Microstructural research published in 2024 reinforces this performance-based direction. Chen *et al*., [16], review identification and mechanical characterization regarding interfacial transition zones, and Xu *et al*., [17], examine micro-mechanical behavior around recycled aggregates and recycled cement paste. Lu *et al*., [25], link transition zones and pore structure to compressive strength. Collectively, the studies indicate that strength loss is not inevitable; it results from moisture state, weak residual mortar, pore connectivity, and interface integrity. This distinction matters for specifications. A prescriptive rule that caps RCA at a low percentage may unnecessarily restrict high-quality material, while an unrestricted recycled-content target may permit poor material. Performance limits for absorption, chloride migration, shrinkage, strength and exposure class provide a more rational route.

Direct reuse should sit above crushing in the circular hierarchy whenever safety and logistics permit. Reusing structural steel sections, façade components, paving units, raised-floor systems, doors, fixtures or precast elements preserves more of the energy and labor already embodied in a product than crushing it into feedstock. The reviewed literature focuses more on recycling than direct component reuse, which is itself an important gap. Saudi giga-projects and urban redevelopment programs could improve reuse by requiring pre-demolition audits, component inventories, deconstruction plans and digital material passports. Reuse is notably beneficial for standardized modular components because quality can be inspected and dimensions can be matched to new designs.

Waste glass provides a second important pathway. Qin *et al*., [19], review glass as aggregate and finely ground powder in cement-based materials. Coarse glass replacement can affect workability and raise alkali-silica reaction concerns depending on particle size and chemistry, whereas finely ground glass can exhibit pozzolanic activity and help form a denser microstructure. The resource-efficiency logic is strongest where locally collected glass is clean, consistently processed and substitutes either quarried sand or a portion of clinker-intensive binder. Saudi applications could include non-structural precast products, terrazzo-like finishes, blocks, controlled concrete mixtures and alkali-activated systems. The key is to match fineness and chemistry to the intended reaction rather than treating all waste glass as equivalent.

Plastics require greater selectivity. Lamba *et al*., [20], and Park *et al*., [21], show that recycled plastics can be incorporated as fibers, lightweight particles or aggregate substitutes, but increasing plastic content frequently reduces density, stiffness and compressive strength because hydrophobic surfaces bond poorly with cement paste. The most credible applications therefore value low density, toughness, crack control, thermal behavior, or waste diversion rather than maximum compressive strength. Examples include non-load-bearing panels, lightweight blocks, drainage elements and selected fiber-reinforced products. Using plastic in concrete should also consider fire behavior, microplastic release, composite recyclability, and whether mechanical recycling into a new polymer product would retain greater material value.

Steel slag and other industrial mineral by-products can substitute natural aggregate where volumetric stability, leaching, and chemistry are controlled. Loureiro *et al.,* [22], identify mechanical and environmental advantages for steel slag and recycled concrete aggregate in pavement applications. For Saudi Arabia, industrial clusters near construction demand create opportunities for industrial symbiosis: slag, mineral fines and other by-products can move from industrial producers to certified construction-material processors. The governance requirement is important. Expansion potential, free lime, heavy metals, grading and aging must be tested so that waste diversion does not transfer risk into infrastructure.

Geopolymer and alkali-activated materials broaden the circular-material portfolio by replacing part or all of Portland cement with chemically activated aluminosilicate precursors. Alhazmi *et al*., [1], provide a useful example by combining recycled aggregate, fly ash, slag and industrial effluents in one geopolymer concrete system. Textile effluent produced higher compressive and split tensile strengths than the freshwater control in that experiment, whereas fertilizer effluent increased chloride migration and acid-related mass loss. The project-level lesson is specific: an input may satisfy an early strength target while still failing a durability or chemical-compatibility gate. Secondary water or industrial by-products should therefore be released for use only after chemistry, setting behavior, corrosion implications and exposure-specific durability are reviewed alongside strength. Waste status cannot function as a proxy for engineering suitability.

4.1 Project-Level Material Approval Protocol

To make the evidence usable on a live project, secondary materials should pass five sequential gates. Gate 1 - source eligibility - records the demolition or industrial source, segregation method, contamination history and intended destination. Gate 2 - material characterization - verifies properties such as grading, density, absorption, composition and contaminants for RCA, or chemistry and stability for industrial by-products. Gate 3 - application assignment - places the material into a risk-appropriate use category rather than allowing a supplier to propose the same product for every work package. Gate 4 - trial validation - requires the actual concrete mixture, precast product, pavement layer or other proposed system to demonstrate specified fresh, mechanical and durability performance. Gate 5 - production control - links approved source, batch records, moisture corrections, test results and installed location through traceable project documentation. The literature on RCA variability, treatment and supplementary binders supports the need for these differentiated controls [2-28].

4.2 Fit-for-Purpose Allocation Rather Than Maximum Recycled Content

A project should allocate secondary materials according to retained value and technical risk. Intact, inspectable components should first be considered for direct reuse because this preserves more embodied value than crushing. Clean concrete-derived RCA with controlled absorption and composition can be evaluated for higher-value pavers, precast products or structural concrete where the project specification permits and trial performance is demonstrated. More variable mixed mineral fractions can be directed to road base, subbase, fill or other lower-risk applications. Residual material that cannot be safely qualified should not be forced into a recycled-content target. This hierarchy converts circularity into an engineering allocation problem and reduces the chance that sustainability targets unintentionally create durability, warranty or rework exposure [2-27].

Table 1: Evidence-based pathways for recycled and reused construction materials

Material stream	Primary route	Resource-efficiency value	Key technical risk	Priority Saudi application
Concrete CDW / RCA	Crush, grade, certify	Avoids quarry aggregate and landfill; enables local closed loops	Absorption, attached mortar, contaminants, chloride durability	Road layers, blocks, pavers; certified structural concrete
Reclaimed components	Inspect and directly reuse	Preserves highest embodied value and avoids reprocessing	Damage, dimensional compatibility, warranties, traceability	Steel sections, precast units, façades, doors, paving
Waste glass	Cullet aggregate or ground powder	Displaces sand or binder; diverts glass from disposal	ASR potential, sharp particles, chemistry variability	Precast finishes, blocks, controlled concrete, geopolymers
Plastic waste	Fibers or lightweight particles	Diverts persistent waste and can reduce density	Weak bond, fire behavior, stiffness loss, end-of-life complexity	Non-load-bearing products, lightweight elements, fibers
Steel slag / mineral by-products	Processed aggregate or binder component	Reduces quarrying and supports industrial symbiosis	Expansion, leaching, free lime, aging requirements	Pavements, road bases, selected concrete products
Recycled water / industrial effluent	Controlled mixing or curing water	Reduces freshwater use and wastewater discharge	Salts, organics, pH, corrosion and setting effects	Unreinforced/controlled mixes after chemical qualification

5. Project Quality Assurance, Durability and Field Control

For project approval, mechanical acceptance is necessary but insufficient. A recycled-material submittal should identify source, processing route, proposed application, declared properties, sampling frequency and applicable test evidence. The level of control should increase with structural consequence and exposure severity. Evidence that 100% recycled aggregate products can perform adequately under controlled manufacturing [26], alongside the variability reported for non-selected CDW [27], supports a quality ladder: low-risk fill may require basic grading and contamination control, whereas reinforced or durability-critical concrete requires tighter source control, trial-mixture verification and exposure-specific acceptance tests. This allows QA/QC effort to be proportional to project risk rather than applying either blanket rejection or blanket acceptance to recycled materials.

For Saudi site conditions, the inspection and test plan should place particular attention on water absorption, moisture condition, shrinkage, chloride penetration, sulfate resistance, thermal exposure and reinforcement corrosion risk. RCA's attached mortar increases accessible porosity, and uncontrolled moisture can distort effective water-to-binder ratio during batching. A practical control sequence is therefore: test incoming aggregate properties; establish moisture correction; approve a trial mixture; verify workability and density; confirm compressive performance; and add chloride or sulfate-related durability tests where the exposure class requires them. Research on interfacial transition zones and supplementary binders indicates that mixture engineering can compensate for RCA weaknesses, but only when the local feedstock and the actual production process are validated [12–25].

The findings of Alhazmi *et al.*, [1], also demonstrate why a project should use multi-criteria release criteria for secondary liquids and waste-derived inputs. Their fertilizer-effluent mixture showed an unfavorable chloride-migration and acid-resistance response despite acceptable strength-related performance. On a project, such a result should trigger restricted use, redesign or rejection rather than approval based on compressive strength alone. The decision matrix should therefore cover fresh properties, mechanical performance, dimensional stability, transport properties, chemical resistance and expected service-life exposure before final approval.

Digital prediction can support material control, but it should sit behind verified project data rather than replace testing. Zhao *et al.*, [30], show the growing ability of machine-learning models to predict RCA concrete properties from material and mixture inputs. In Saudi projects, a more immediately useful application is a traceable dataset connecting source lot, absorption, grading, moisture condition, mixture proportions, test results and installed location. Over time, such records can support calibrated prediction and supplier benchmarking. During execution, however, model outputs should remain advisory until they are validated against local aggregates, hot-weather production, curing practice, salinity and exposure conditions.

6. Environmental and Economic Resource Efficiency

Environmental performance depends on the complete system boundary. Recycling usually reduces quarry extraction and landfill demand, but crushing, washing, treatment and transport consume energy. Marinković *et al.*, [5], argue that sustainability assessment of recycled aggregate concrete must consider structural function and service life rather than compare mixtures only per cubic meter. Haider *et al.*, [7], reach a similar conclusion from the waste-management side: higher CDW recovery in Riyadh can reduce environmental burdens, yet the result depends on the treatment chain and avoided processes. The correct functional unit may therefore be a square meter of floor, a kilometer of pavement, or a structural element delivering a defined service life, not simply one tonne of recycled material.

Carbonation treatment creates an additional opportunity because recycled concrete can absorb carbon dioxide while improving aggregate quality. Emerging life-cycle studies show that accelerated carbonation can lower impacts compared with some conventional RCA treatments, although electricity source, CO2 supply, transport and allocation assumptions strongly affect results. The practical lesson for Saudi Arabia is to co-locate treatment with demolition hubs, concrete plants or industrial CO2 sources where feasible. Circular clusters reduce haulage and make by-product exchange easier.

Economic analysis should be undertaken at project decision level rather than by comparing only the supplier price per tonne. A practical 'total landed and controlled cost' comparison should include purchase price, crushing or treatment, transport, testing, storage, moisture management, additional binder or admixture demand, yield loss and expected rework risk; it should then credit avoided disposal charges, avoided virgin-material purchase and any recoverable material value. Alhazmi *et al.*, [1], reported a lower material cost for its recycled aggregate geopolymer system than the conventional comparison, but project teams should not generalize that result without local prices and logistics. The most important sensitivity variable for heavy mineral materials is often distance: a low-cost recycled aggregate may lose both financial and environmental advantage when hauled far from the source. Procurement decisions should therefore compare alternatives by functional unit and delivered performance, not purchase price or recycled percentage alone [5-7].

7. Implementation Framework for Saudi Project Delivery

The proposed Saudi project workflow begins before procurement. During design, teams should identify where material quantities can be reduced, where components could be designed for disassembly, and which work packages are technically suitable for secondary materials. Before demolition or site clearance, a resource audit should classify reusable components and recyclable streams. During mobilization, the construction team should define segregation zones, contamination controls, temporary storage, haul routes and approved recovery destinations. These steps treat source separation as an engineering input to later material quality, directly responding to the implementation barriers identified in Saudi circular-economy and mega-project research [8-24].

The second layer is formal product qualification. The materials engineer and QA/QC function should review source declarations, test certificates and proposed application limits, then define any trial or project-specific testing needed before approval. Procurement should place only conditionally approved suppliers or processors on the sourcing route, with purchase orders linked to the same source and quality requirements used during technical approval. For concrete and precast applications, the approved mixture should specify how RCA moisture is measured and corrected, how substitutions are controlled, and which durability indicators are required for the exposure class. This closes a common gap between technical approval and commercial purchase, where the lowest-price material can otherwise enter the project with different source quality from the tested sample.

The third layer is execution control and supply reliability. Long-term framework agreements can support investment in washing, sorting, mobile crushing, carbonation or laboratory control, but project value depends on consistent deliveries. Each incoming lot should therefore be traceable to an approved source and accompanied by the required quality evidence. Site teams need defined hold points for non-conforming loads, while project controls should record quantities accepted, rejected, reused and diverted. For large developments, on-site or nearby recovery hubs can shorten logistics loops and make it easier to return processed material to the same project area, strengthening both cost and environmental performance.

The fourth layer is project measurement and close-out. A useful dashboard should report virgin aggregate avoided, clinker avoided where relevant, percentage of components directly reused, CDW diversion, secondary-material yield, average haul distance, rejected-load rate, test pass rate, embodied carbon per functional unit, water use, cost variance and percentage of traceable batches. These metrics connect sustainability outcomes to operational performance. A high recycling tonnage accompanied by frequent rejection, long haulage or increased cement demand would indicate that the project is shifting rather than solving resource inefficiency. Close-out records should preserve approved sources, batch evidence and installed locations so that future maintenance, deconstruction and reuse decisions have reliable material information.

7.1 Responsibility Map across the Project Lifecycle

The framework assigns decisions to the functions that already manage project delivery. Design teams define acceptable applications and exposure requirements; sustainability teams set measurable circularity objectives; materials engineers evaluate technical suitability; QA/QC converts those requirements into inspection and test points; procurement controls approved suppliers and contractual evidence; construction teams maintain segregation and source integrity; and project controls consolidate quantity, cost and KPI data. The key management principle is that no single sustainability function should 'own' recycled materials in isolation. Approval must travel through the same design, procurement, quality and site-control chain as any other construction material, with additional source and circularity evidence where needed.

7.2 Worked Project Decision Scenario

Consider a hypothetical Saudi urban redevelopment project generating demolished concrete while simultaneously requiring road subbase, paving products and new reinforced concrete. The proposed sequence would first segregate clean concrete from gypsum, soil, timber and mixed debris. After crushing, a representative RCA sample would be tested for grading, density, absorption and contamination. If the source shows high variability, the material could be allocated to subbase after project-specific compaction and performance checks rather than being forced into structural concrete. A cleaner, controlled fraction could proceed to a paver or concrete trial. Only after the trial satisfies the specified fresh, strength and exposure-related criteria would procurement release the source for production. Incoming loads would then be matched to the approved source and monitored for moisture and quality drift. This scenario illustrates how one demolition stream can be split into different value pathways rather than assigned a single blanket recycling destination.

7.3 Decision Escalation for Non-Conforming Secondary Materials

A practical framework also needs a defined response when secondary material fails a gate. Minor grading or moisture deviations may be corrected through reprocessing or controlled batching; contamination, unstable chemistry or repeated durability failure should trigger quarantine and reassignment to a lower-risk application or rejection. The project should document the reason for reassignment so that sustainability reporting does not count material as successfully recycled merely because it remained on site. This escalation logic protects engineering performance while still seeking the highest safe recovery route for each material stream.

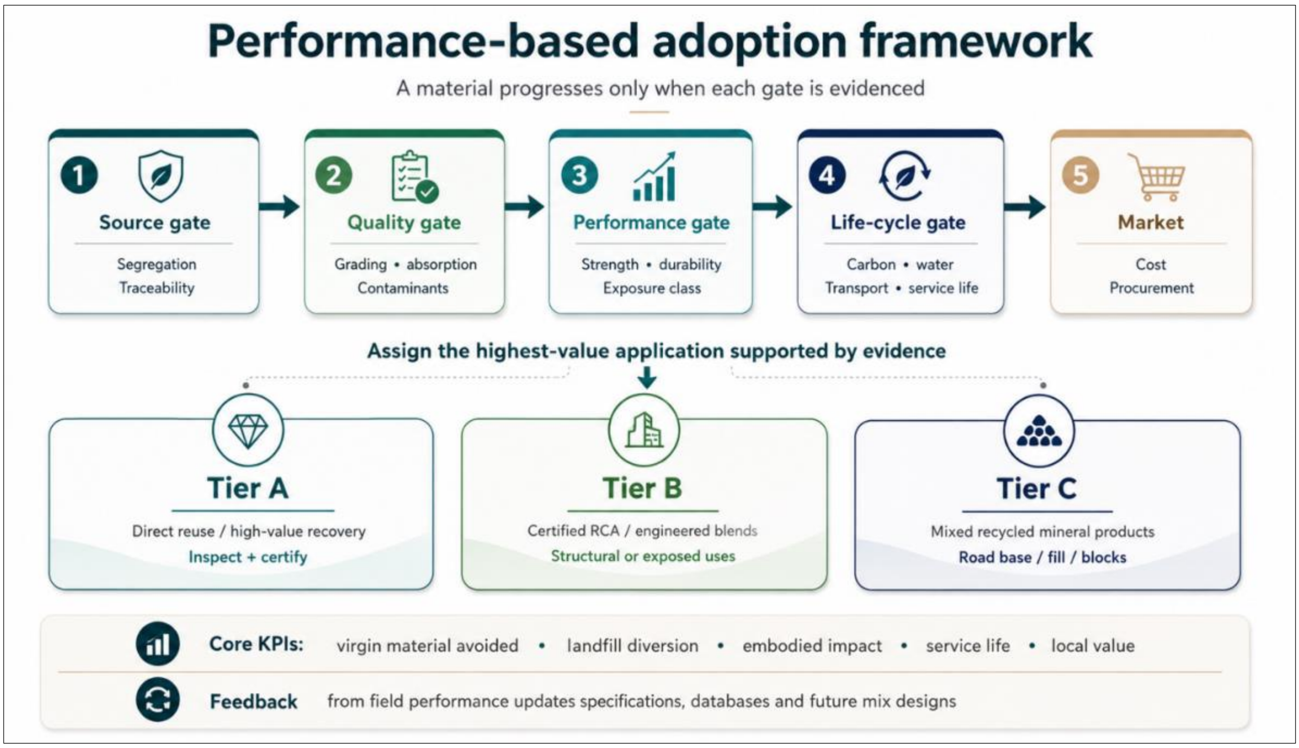

Figure 2: Stage-gate adoption and application-tier framework for secondary construction materials in Saudi Arabia

Table 2: Role-based project implementation and control matrix for secondary construction materials

Project stage	**Accountable / lead functions**	**Required evidence or decision**	**KPI / hold point**
Design and specification	Design + Sustainability	Define permitted applications, exposure limits, performance criteria and circularity targets	Approved specification; applications screened for reuse/recycling
Source audit / demolition	Construction + Materials	Segregation plan, source history, contamination control, reusable-component inventory	Contamination rate; % directly reusable components
Material qualification	Materials + QA/QC	Representative sampling, grading, absorption/density, composition and application-specific tests	Qualification pass rate; approved source lots
Procurement release	Procurement + Materials	Approved supplier/source, technical submittal alignment, traceability clauses, logistics distance	% purchases from approved sources; average haul distance
Production / installation	Site + QA/QC	Moisture correction, trial/production test results, lot traceability, NCR control	Test pass rate; rejected-load rate; % traceable batches

Project stage	Accountable / lead functions	Required evidence or decision	KPI / hold point
Close-out and reporting	Project Controls + Sustainability	Installed quantities, avoided virgin material, diversion, cost and life-cycle evidence	Virgin material avoided; diversion; cost variance; kg CO2e/function

8. Research Gaps and Priority Agenda

Five research priorities emerge. First, Saudi Arabia needs a representative material-flow database for concrete, asphalt, masonry, glass, gypsum, metals, and excavation materials across major cities and project types. Without reliable quantities and quality distributions, recycling capacity as well as market demand cannot be planned efficiently. Second, locally sourced RCA should be tested under Saudi exposure conditions, including hot-weather production, chloride-rich environments, aggressive soils and realistic curing practices. Laboratory evidence from temperate regions cannot simply be transferred without validation.

Third, comparative studies should evaluate direct reuse, conventional recycling, advanced treatment and virgin replacement using the same functional unit and service-life assumptions. This would prevent technological enthusiasm from being mistaken for environmental benefit. Fourth, research should examine procurement behavior, warranty allocation and contractor risk because technical standards alone may not produce uptake. Demonstration projects should publish both successful and unsuccessful results, creating confidence through evidence rather than promotional claims.

Fifth, digital tools should connect circular design with operations. Building information modeling, material passports, pre-demolition inventories and machine-learning quality prediction can support matching between available secondary materials and upcoming demand. Yet digitalization must be linked to physical testing and auditable data. The most useful Saudi research program would therefore combine material science, life-cycle assessment, logistics optimization, standards development and behavioral research within shared pilot projects. Such interdisciplinary evidence can move recycled construction materials from isolated trials into routine, bankable supply chains.

A priority for future Saudi research is to test this type of project-control framework in real work packages rather than only in laboratory mixtures. Demonstration projects should report the full decision chain: material origin, segregation quality, processing yield, approval tests, procurement price, haul distance, production variability, rejection rate, installed application and field performance. A national specification program should distinguish material acceptance from product acceptance because a compliant recycled aggregate can still perform poorly in an unsuitable mixture, while a carefully engineered mixture may safely accommodate variable feedstock within controlled limits. Round-robin testing among Saudi laboratories would help establish the repeatability of absorption, chloride migration, sulfate resistance, abrasion and contamination measurements. Field monitoring should then compare recycled and conventional reference sections under hot-weather batching, curing interruptions, coastal aerosols and aggressive soils. Economic studies should also examine how gate fees, quarry prices, fuel cost, landfill restrictions and guaranteed offtake alter viability across Riyadh, Jeddah, the Eastern Province and emerging development corridors. This combination of technical, commercial and site data would make future guidance directly usable by project engineers, materials teams, procurement managers, QA/QC staff and sustainability functions.

9. CONCLUSIONS

Resource-efficient construction materials can contribute materially to Saudi Arabia's circular built environment, but the central project question is not whether a product contains recycled material; it is whether the proposed secondary input can be traced, qualified, allocated to the correct application and controlled through delivery and service life. The reviewed evidence shows that RCA, reclaimed components, waste-derived binders, glass, selected plastics, steel slag and recycled water can reduce virgin-resource demand when source quality, processing, mixture design, logistics and exposure are controlled. The same evidence also shows why generalized claims are risky: feedstock variability, attached mortar, chemical composition, transport distance and durability requirements can change the outcome substantially [1-18].

For Saudi Vision 2030, the recommended pathway is a stage-gate project system: audit the source, segregate the stream, characterize the material, assign a fit-for-purpose application, validate the product or mixture, release only approved suppliers, control production, and retain traceable close-out data. The distinctive contribution of this review is the translation of circular-construction evidence into responsibilities, hold points and KPIs that can be embedded in routine project delivery. This approach makes recycling and reuse relevant to current construction responsibilities because it connects sustainability objectives with material submittals, procurement decisions, QA/QC testing, site logistics, non-conformance control and project reporting. Resource efficiency becomes credible when a project can demonstrate not only how much material was recycled, but where it came from, why it was technically accepted, where it was used, what virgin input it displaced, how it performed, and whether the whole decision reduced cost and environmental burden without transferring risk to durability or safety.

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