



Circular Economy and Construction Waste Management in Saudi Mega-Projects: Pathways Towards Vision 2030 Sustainability Targets

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Abstract: Saudi Arabia's Vision 2030 is accelerating the delivery of large-scale urban, tourism, transport, industrial and infrastructure projects while simultaneously strengthening national ambitions for environmental protection, resource efficiency and waste diversion. The scale of this development creates a strategic challenge: construction and demolition waste cannot be managed only as an end-of-pipe disposal problem. It must be addressed through a circular economy model that prevents waste, preserves material value, enables reuse and high-value recycling, and creates dependable markets for secondary construction materials. This paper develops a Saudi-contextualised pathway for integrating circular economy principles with construction waste management in mega-projects. A structured narrative review was undertaken using recent peer-reviewed literature, Saudi policy and regulatory sources, international circular-economy standards, and contemporary research on digital construction and material passports. The review identifies persistent barriers including fragmented responsibilities, limited lifecycle awareness, insufficient source segregation, inconsistent quality assurance for recovered materials, weak secondary-material demand, data gaps, and inadequate contractual incentives. In response, the paper proposes an integrated Circular Construction and Waste Management Framework organised around six linked stages: prevention and demand reduction; circular design; circular procurement; construction-stage segregation and control; recovery and quality assurance; and reintegration of secondary materials into new projects. Digital traceability, governance, market development and performance measurement operate across all stages. The framework introduces practical indicators for material efficiency, waste intensity, source segregation, diversion, reuse, recycled content and traceable recovery. Saudi Arabia's reported rise in national waste diversion from 5% in 2018 to 18% in 2025, alongside a national 90% diversion target by 2040, demonstrates the wider policy direction in which construction circularity must operate. The study concludes that mega-projects can become demand anchors for circular material markets when client specifications, design decisions, contractor controls, recycling infrastructure and digital information systems are aligned. Empirical validation across active Saudi projects is recommended to quantify sector-specific benchmarks and test the proposed indicators.

Keywords: Circular economy; construction and demolition waste; Saudi Arabia; Vision 2030; mega-projects; construction waste management; material passports; BIM; resource efficiency; recycling; secondary materials.

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1. INTRODUCTION

Saudi Arabia is reshaping its built environment through an exceptional portfolio of major infrastructure, urban-development, tourism, housing, transport and industrial investments. These projects are central to Vision 2030 because they support economic diversification, quality of life, new destinations and improved national infrastructure. At the same time, the national development model increasingly emphasises environmental sustainability, more efficient use of resources and a transition away from disposal-dependent waste management. The Vision 2030 Annual Report 2025 identifies circular economy as a key approach to resource management and reports that national waste diversion from landfill increased from 5% in 2018 to 18% in 2025, with a stated target of 90% by 2040 (Saudi Vision 2030, 2026). The report also highlights an expanding ecosystem of licensed entities and recycling facilities. These trends create a policy environment in which mega-projects are expected not only to deliver physical assets but also to contribute to long-term resource efficiency.

Construction has a particularly important role in this transition. It is material-intensive, geographically dispersed and capable of generating large volumes of excavation material, concrete, asphalt, steel, timber, packaging, gypsum, plastics and mixed waste. Demolition and refurbishment add further streams containing both recoverable and potentially hazardous materials. In a linear model, virgin materials are extracted, transformed into products, installed, used and eventually discarded. This approach transfers environmental impacts upstream through quarrying, cement and steel production and downstream through transport, landfilling and illegal dumping. It also destroys residual economic value that could remain embedded in components and materials.

Saudi research indicates that the shift toward circular construction is still developing. Blaisi (2019) documented challenges in construction and demolition (C&D) waste management in Saudi Arabia and argued for stronger recycling, recycled-material adoption and enforcement. More recent studies focused specifically on Saudi mega-projects. Alotaibi et al. (2024a) found that important barriers include gaps in regulation, education, awareness, guidance and incentives, while Alotaibi et al. (2024b) identified regulatory frameworks, professional education, technology, market maturity and institutional support as major enablers. AlJaber et al. (2024) similarly found that awareness and attitudes affect circular-economy implementation in the Saudi building sector. Collectively, this literature shows that the challenge is no longer whether circular

economy is relevant, but how to operationalise it in project decisions.

The National Center for Waste Management (MWAN) provides an institutional basis for this shift. Its mandate explicitly includes regulating and supervising waste-management activities, encouraging investment and adopting circular-economy principles. Saudi implementing regulations define construction and demolition waste broadly to include waste from building and infrastructure construction, demolition, maintenance, renovation, rehabilitation and refurbishment, including concrete, bricks, excavation materials, timber, iron, plastics and potentially hazardous materials (MWAN, 2026). This definition is important because it makes circularity a lifecycle and infrastructure issue rather than a narrow building-site housekeeping activity.

The central research problem addressed in this paper is the absence of a fully integrated, project-level pathway that connects circular design, procurement, site waste controls, recovery infrastructure, digital traceability and secondary-material markets to Vision 2030 sustainability objectives. The objective is therefore to develop a practical framework for circular economy and construction waste management in Saudi mega-projects, supported by measurable indicators and an implementation roadmap. The paper asks four questions: (1) what are the dominant barriers and enablers for circular construction in Saudi Arabia; (2) at which project stages can waste and material losses most effectively be prevented; (3) how can digital information and market mechanisms support closed-loop material flows; and (4) which indicators can enable clients and contractors to measure progress without reducing circularity to a single recycling percentage.

The contribution is conceptual and decision-oriented. Rather than claiming empirical performance results, the paper synthesises current evidence and translates it into a framework that can subsequently be tested across active projects. This distinction is important for academic integrity: numerical targets proposed later in the paper are examples for project governance unless explicitly attributed to an official source.

2. Conceptual Foundations: From Waste Management to Circular Construction

Circular economy changes the unit of analysis from “waste after generation” to “value throughout the material lifecycle.” ISO 59004:2024 defines a general set of circular-economy principles and implementation guidance, while ISO 59010:2024 focuses on the transition of business models and value networks and ISO 59020:2024 provides

requirements and guidance for measuring circularity performance. Together, these standards support three important shifts for the construction sector: first, avoiding unnecessary resource consumption before waste is created; second, retaining the functional and economic value of products and materials for as long as possible; and third, using measurement systems that distinguish high-value circular strategies from simple disposal diversion.

This distinction matters because conventional waste hierarchies are sometimes implemented too narrowly. Recycling is beneficial when it substitutes virgin material and meets technical requirements, but it may still involve significant processing, transport and value loss. Reuse of a component generally preserves more embodied value than crushing it into aggregate; adapting an existing asset may preserve more value than demolishing and recycling it; and eliminating an unnecessary material through design can be preferable to managing it efficiently as waste. A circular project therefore applies a hierarchy of decisions: refuse unnecessary material demand, reduce quantities, extend asset life, design for adaptability, reuse components, remanufacture where feasible, recycle materials at high quality, recover remaining value, and dispose only when no safe and viable circular route exists.

In the built environment, circularity is constrained by long asset lives and complex ownership. Materials installed today may not be recovered for decades, meaning that information must travel with the asset. Material passports and BIM-linked records have therefore become important research areas. Atta et al. (2021) demonstrated a digital material-passport approach linked to BIM, while Honic et al. (2021) showed how material passports can support end-of-life recycling assessment. More recent studies extend these concepts to data requirements, disassembly planning, digital product passports and openBIM-enabled demolition planning (Kuzminykh et al., 2024; Sanchez et al., 2024). Digitalisation does not create circularity by itself, but it reduces information asymmetry by recording what materials are present, where they are located, their condition, potential hazards and possible recovery pathways.

Construction waste management remains an essential operational layer. Source segregation protects the quality of recoverable streams. Contamination between concrete, timber, gypsum, metal, plastics, soil and hazardous materials can convert a potentially valuable resource into mixed waste with limited recovery options. Ramos et al. (2023) emphasise local infrastructure, supervision, training and procedural control as important

conditions for effective C&D waste management. In Saudi Arabia, these issues are amplified by the scale and speed of mega-project delivery, long logistics chains, multiple contractors and extensive temporary works.

The economic dimension is equally important. Circular materials need buyers. If specifications automatically favour virgin materials, recycled aggregates and reused components may remain technically available but commercially stranded. Large Saudi clients can influence this market by setting minimum performance requirements, permitting approved recycled alternatives, creating take-back arrangements and aggregating demand across project packages. In this sense, mega-projects can function as “market makers”: they generate recoverable material at scale while also purchasing large quantities of construction products. A circular procurement strategy connects these two sides of the system.

Finally, circular construction must remain compatible with safety, quality and environmental protection. Hazardous substances, contamination, unknown provenance and variable material quality can limit reuse. Research on demolition waste shows that hazardous content is a management challenge requiring identification and testing rather than a reason to reject circularity altogether. The principle should therefore be “safe circularity”: retain value where technical, health, environmental and legal conditions are satisfied, and maintain controlled treatment or disposal routes where they are not.

3. Saudi Arabia: Policy, Infrastructure and Mega-Project Context

Saudi Arabia’s circular-economy transition is supported by a developing institutional and infrastructure base. MWAN regulates and supervises the waste sector with an explicit circular-economy orientation. The Waste Management Law and its implementing regulations provide a national foundation for classifying, transporting, treating and managing waste streams. For construction and demolition waste, this regulatory context creates obligations that can be translated into project procedures such as approved waste contractors, documented movements, designated storage areas, segregation rules and evidence of final treatment.

Vision 2030 provides the broader sustainability narrative. The 2025 annual report states that circular economy has been adopted to support sustainable growth and resource efficiency, with investment in recycling and waste-management infrastructure. It reports 1,300+ licensed entities, 145 recycling facilities, national waste diversion of 18% in 2025 compared with 5% in 2018, and a 90%

waste-diversion target by 2040. These are national figures, not construction-specific performance results; nevertheless, they establish an important direction for the construction sector because C&D waste is one of the largest material streams generated by urbanisation and infrastructure growth.

Saudi Investment Recycling Company (SIRC) has also developed C&D recycling capacity. SIRC has described a Riyadh facility designed to process approximately 600 tonnes of construction and demolition waste per hour, with recycled aggregates intended for construction, roads and infrastructure. The significance of such facilities is not only their processing capacity. They create a potential supply of secondary aggregates and demonstrate the need for project specifications and quality-assurance systems capable of absorbing recycled outputs. Circularity therefore depends on both waste-side infrastructure and demand-side procurement.

Saudi mega-projects present unusual opportunities. Large clients can standardise requirements across multiple contractors, mandate digital reporting, establish central material-recovery areas, negotiate reverse-logistics agreements and create internal exchanges for surplus materials. They can also influence designers early enough to reduce excavation, rationalise structural grids, optimise temporary works, adopt modular construction and specify products with recycled content. Conversely,

the scale of mega-projects creates risk: if circularity is introduced only after construction has started, the project may generate large waste volumes faster than local recovery systems can absorb them.

The academic literature reflects this tension. Alotaibi et al. (2024a) surveyed 239 participants across three Saudi mega-project case studies and identified barriers including regulatory gaps, limited education and awareness and insufficient incentives. In a companion study using interviews across building, urban-development and infrastructure cases, Alotaibi et al. (2024b) found that circular-economy awareness often concentrates on reuse, recycling and waste reduction rather than whole-lifecycle circularity. Their proposed enablers—regulation, education, technology, market maturity and institutional support—closely match the systems perspective adopted in this paper. A subsequent framework study by Alotaibi et al. (2024c) further emphasised coordinated implementation in mega-scale construction.

This evidence suggests that Saudi Arabia does not lack circular-economy ambition. The implementation gap lies in converting ambition into project controls, commercial mechanisms, information systems and market transactions. Therefore, a useful framework must bridge policy and site practice rather than treating them as separate domains.

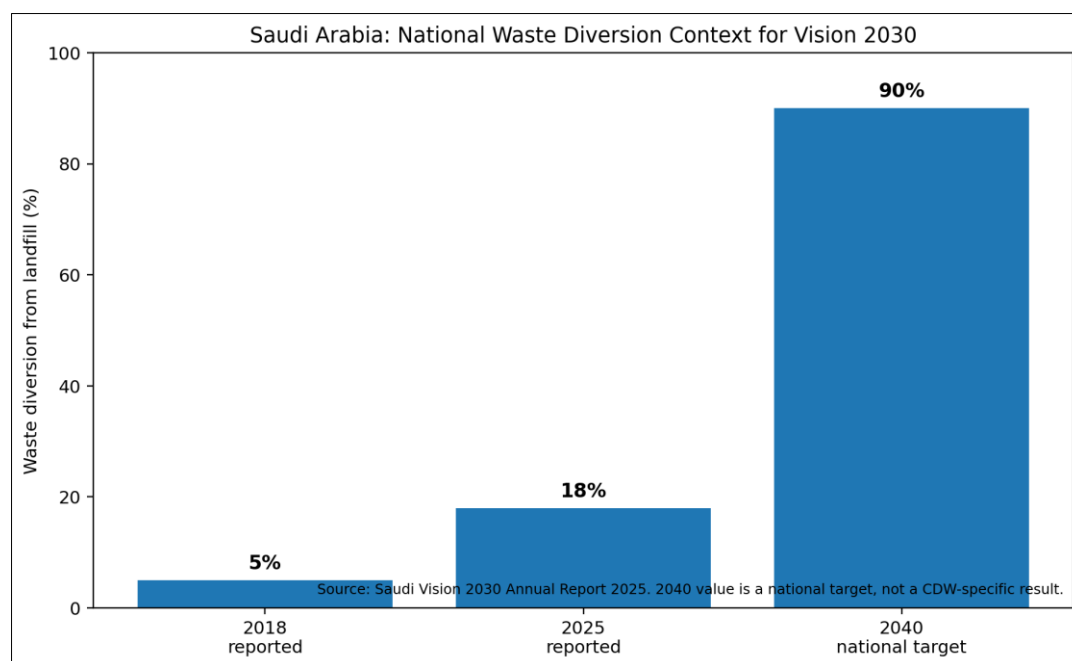


Figure 1: National waste-diversion context reported in the Saudi Vision 2030 Annual Report 2025. The 2040 value is a national target and is not a construction-waste-specific project result

4. METHODOLOGY

This research adopts a structured narrative review and conceptual-framework development

approach. The method was selected because the objective is to integrate policy, standards and multidisciplinary construction research into a

practical decision framework rather than to estimate a pooled statistical effect. The evidence base prioritised literature published from 2020 onward, while retaining selected earlier Saudi studies where they provide foundational sector context. Sources were identified around five themes: Saudi construction and demolition waste; circular economy in Saudi construction and mega-projects; circular construction and demolition management internationally; digital technologies and material passports; and circularity measurement and governance.

Official sources were used to establish the Saudi policy context. These included the Vision 2030 Annual Report 2025, MWAN regulatory material, SIRC information on C&D recovery infrastructure, and the ISO 59000 family of circular-economy standards. Peer-reviewed studies were used to identify barriers, enablers, technologies, waste-management strategies and measurement approaches. The review did not use a formal systematic-review claim and therefore does not report artificial database screening counts. Instead, literature was selected for direct relevance to the research questions and its ability to inform framework components.

The synthesis followed four analytical steps. First, recurrent problems were coded into governance, design, procurement, construction operations, market, information and behavioural categories. Second, circular strategies were mapped to the project lifecycle to identify when each intervention has the highest leverage. Third, enabling mechanisms were linked to the responsible actor—client, designer, contractor, supplier, waste operator, regulator or asset operator. Fourth, candidate performance indicators were developed to distinguish prevention, reuse, recycling, procurement and traceability outcomes.

The resulting framework is normative: it sets out what a robust circular construction system should contain based on current evidence. It should not be interpreted as proof that the framework has already achieved measured outcomes in Saudi projects. Empirical validation is proposed through Delphi review, expert interviews, contractor surveys and pilot applications using real project material-flow data.

5. Findings from the Literature: Barriers, Enablers and Intervention Points

The literature indicates that circular construction is a systems problem rather than a single technology problem. The first barrier is governance fragmentation. Waste is often treated as the contractor's operational responsibility, while

designers, procurement teams and package managers make earlier decisions that determine material intensity and recoverability. When responsibilities are separated, designers may have no incentive to reduce waste, procurement may not permit secondary materials, and contractors may be judged mainly on disposal compliance. Circularity requires a shared governance model in which the client establishes objectives and allocates responsibilities throughout the value chain.

A second barrier is the timing of intervention. Most value is determined before construction. Design decisions influence excavation volumes, structural material quantities, standardisation, off-site manufacturing, adaptability and future disassembly. Once materials arrive on site, the remaining options are narrower. Waste-management plans are therefore necessary but insufficient. The project must add a circular-design review at concept, schematic and detailed design stages. This review should question whether the asset can meet its function with less material, whether existing structures can be retained, whether dimensions can be standardised, whether components can be assembled reversibly, and whether materials have viable end-of-life pathways.

A third barrier is poor segregation and contamination. High-value recovery requires clean streams. Concrete mixed with soil, gypsum, food waste or hazardous residues may have lower recycling value. Metals are generally easier to recover because mature markets exist, while composite materials and contaminated demolition waste can be more difficult. Source-segregation plans should therefore be designed around expected waste quantities and local outlets rather than generic coloured-bin systems. For mega-projects, dedicated recovery zones, weighbridges, container standards and digital manifests may be justified.

A fourth barrier is uncertainty regarding secondary-material quality and acceptance. Engineers and asset owners carry performance and liability risks. Recycled products must therefore be supported by testing, specifications, certification, traceability and defined use cases. Recycled aggregate, for example, may be appropriate for certain road, backfill or non-structural applications depending on applicable standards and project requirements. The circular approach is not to lower quality thresholds; it is to create evidence that qualified secondary materials can meet them.

The fifth barrier is weak market coordination. Waste generators and material users may operate under different contracts, locations and schedules. A material may be reusable in principle

but not at the moment another project needs it. Digital exchanges, framework agreements, central storage, supplier take-back programs and inter-package material matching can reduce this temporal mismatch. Lu et al. (2023) show how material-passport concepts can reduce information asymmetry in construction-waste trading, while wider digital-construction research identifies BIM, digital twins, RFID and blockchain as potential enablers of traceability.

A sixth barrier is measurement. A single diversion rate can reward low-value outcomes. If 90% of mixed concrete waste is crushed for low-grade fill, a project may report excellent diversion while still consuming large quantities of virgin high-value materials. Circularity indicators should

therefore distinguish prevention, direct reuse, preparation for reuse, closed-loop recycling, downcycling, recovery and disposal. ISO 59020:2024 supports a more structured approach to measuring circularity within a defined system boundary.

The final barrier is organisational capability. Circular construction changes commercial routines. Quantity surveyors need to account for residual value; procurement teams need supplier take-back criteria; designers need disassembly and material-efficiency skills; site teams need segregation discipline; and sustainability teams need data-analysis capability. Training must therefore be role-specific and tied to contractual responsibilities rather than limited to general environmental awareness.

Table 1: Synthesis of recurring circular-construction barriers and implications for Saudi mega-project delivery

Theme	Evidence from literature / Saudi context	Implication for mega-projects
Governance	Fragmented responsibilities and weak incentives repeatedly identified as barriers.	Set client-level circularity requirements and assign lifecycle ownership.
Awareness and capability	Saudi studies report gaps in awareness, education and guidance.	Role-specific training for designers, procurement, site teams and commercial staff.
Design	Waste prevention opportunities are strongest before construction.	Material-efficiency and design-for-disassembly reviews at design gates.
Site segregation	Clean streams retain higher recovery value; contamination reduces options.	Forecast waste streams and provide dedicated segregation/logistics controls.
Secondary-material market	Market maturity and demand are key enablers.	Use recycled-content specifications, quality criteria and framework agreements.
Digital information	BIM, material passports and traceability reduce information gaps.	Connect material data, waste manifests and asset records.
Measurement	Diversion alone can conceal downcycling and high material demand.	Report prevention, reuse, recycling, recycled content and traceability separately.

6. Proposed Circular Construction and Waste Management Framework

The proposed framework contains six lifecycle stages supported by four cross-cutting enablers. It is intended for major Saudi infrastructure and building projects but can be scaled to smaller programs.

Stage 1 — Prevent and reduce material demand. The highest-priority action is to avoid creating waste. At feasibility and concept design, project teams should challenge over-specification, unnecessary finishes, excessive excavation, redundant temporary works and conservative material allowances. Digital quantity take-offs can compare design options using material intensity per functional unit. Lean planning and design coordination can reduce rework. Existing assets and excavated materials should be treated as resources before new materials are procured.

Stage 2 — Design for circularity. Circular design includes adaptability, modularity, standardisation, durability, repairability and disassembly. Not every infrastructure asset can be designed for disassembly, but even long-life assets contain replaceable systems and temporary components. Connections, access and modular replacement strategies can preserve component value. Designers should also specify materials with known composition and recovery routes. Where justified, BIM objects can carry material-passport information including product identity, quantity, recycled content, maintenance requirements and end-of-life options.

Stage 3 — Circular procurement. Procurement converts design intent into market demand. Tender requirements should identify permitted recycled materials, recycled-content expectations, packaging-reduction measures, supplier take-back schemes and evidence requirements. Bid evaluation can award value to circular proposals where technically

compliant. Contracts should prevent perverse incentives in which disposal costs are reimbursed without encouraging prevention. Framework agreements with recyclers and secondary-material suppliers can improve market certainty.

Stage 4 — Construction-stage segregation and control. Contractors should prepare a project-specific C&D waste and materials-management plan before mobilisation. The plan should forecast major streams, identify storage and segregation arrangements, list approved destinations, define hazardous-waste controls, describe weighing and manifest procedures and assign responsibilities. Site logistics should protect recovered materials from contamination and weather damage. Supervisors should verify segregation performance during routine inspections, while dashboards should track waste intensity and recovery by package.

Stage 5 — Recovery, quality assurance and valorisation. Materials leaving the site should follow the highest feasible value pathway. Direct reuse on the same project or another approved project is preferred where safe and technically acceptable. Reprocessing should produce documented secondary products rather than anonymous “waste.” Quality

assurance is central: sampling, testing, grading and certificates should allow engineers to accept outputs for defined applications. Hazardous or contaminated materials require specialised routes and must not be introduced into circular supply chains without appropriate controls.

Stage 6 — Re-enter the market and retain information. Circularity is completed only when recovered value re-enters productive use. Project owners can facilitate this through internal material exchanges, approved supplier lists, recycled-content procurement and data sharing. For permanent assets, as-built BIM and asset information should preserve material data for future maintenance, refurbishment and deconstruction. This transforms today’s project documentation into tomorrow’s urban-mining database.

Four cross-cutting enablers apply to every stage. Governance defines ownership and escalation; digital traceability provides reliable material data; market development creates viable outlets and demand; and performance measurement prevents circularity from becoming a qualitative aspiration. Figure 1 summarises the pathway.

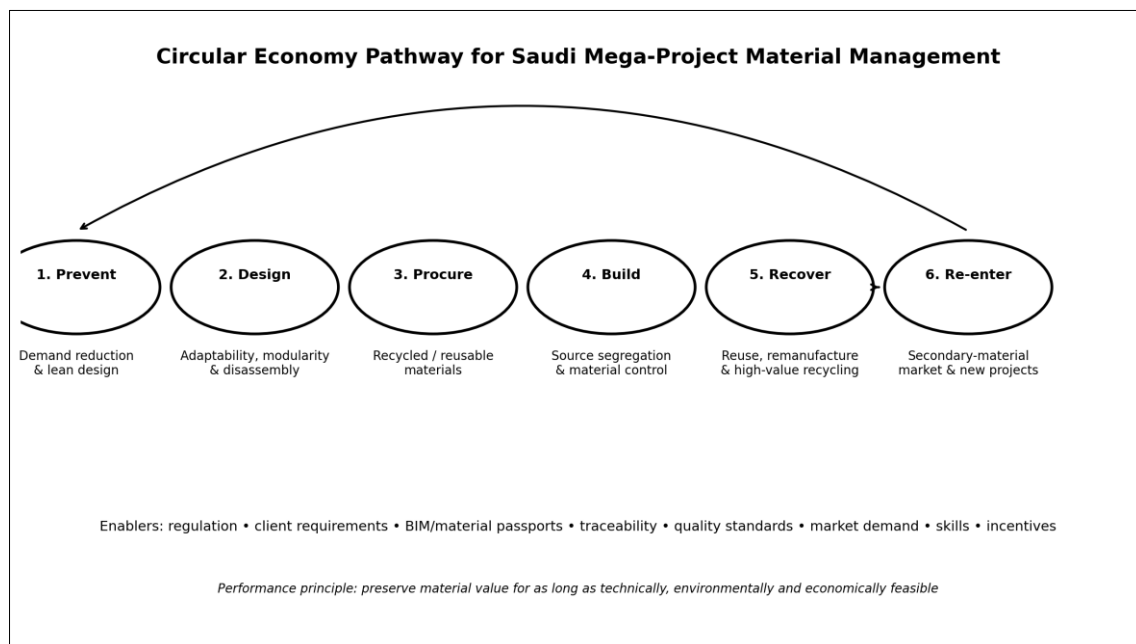


Figure 2: Proposed circular economy pathway for material management in Saudi mega-projects

Table 2: Lifecycle intervention points for circular construction and waste management

Lifecycle stage	Priority circular actions	Primary evidence / output
Feasibility & concept	Retain existing assets; reduce scope/material demand; balance cut/fill; plan material flows.	Material baseline; option comparison; preliminary circularity strategy.
Design	Standardise; modularise; design for adaptability/disassembly; select recoverable materials.	Circular design review; BIM quantities; material/passport fields.

Lifecycle stage	Priority circular actions	Primary evidence / output
Procurement	Permit recycled alternatives; require recycled content; take-back; packaging reduction.	Tender clauses; supplier declarations; approved secondary-material list.
Construction	Source segregate; prevent damage; reuse excavated/material surplus; control rework.	Waste forecast; manifests; weighbridge data; inspection records.
Recovery	Test, grade and certify outputs; maximise direct reuse and high-value recycling.	Quality certificates; reuse approvals; recycler evidence.
Handover & operation	Retain material information; plan repair, replacement and future recovery.	Asset data; material passports; deconstruction guidance.

7. Performance Measurement and Circularity Indicators

A robust measurement system should answer three questions: how much material demand was avoided, how much generated material retained value, and how much procurement demand shifted toward secondary or reusable resources. Indicators should be calculated within a clearly defined project boundary and should not combine unlike outcomes without explanation.

Material intensity can be expressed as tonnes of major material per functional unit—for example, tonnes of concrete per square metre of floor area or per kilometre of infrastructure—provided comparisons are made between functionally comparable designs. Prevention can be estimated as the difference between an approved baseline and the final design quantity, with a documented basis. Waste intensity can be reported as kilograms or tonnes of waste per unit of constructed output. Source-segregation rate measures how much waste is separated into defined clean streams before leaving the site.

The diversion rate is useful but should be decomposed. A project dashboard should show direct reuse, preparation for reuse, recycling, other recovery and disposal separately. Recycled-content rate measures the mass share of secondary material

in purchased products or selected material categories. Circular procurement coverage can measure the percentage of relevant contracts containing approved circular-economy requirements. Traceability completeness can measure the share of waste or recovered materials supported by verified digital records from generation to destination.

Quality and value retention also matter. For example, the percentage of recovered concrete returned to construction-grade applications is more informative than total concrete diversion alone. Likewise, reusable components should be tracked separately from materials that are crushed or melted. The aim is to progressively shift the portfolio upward in the value hierarchy.

Targets should be project-specific. A rail project, coastal development and high-rise urban district have different waste profiles and local markets. Saudi clients should therefore establish corporate minimum requirements but allow packages to set evidence-based targets after waste forecasting and market assessment. This avoids arbitrary targets while maintaining ambition. Where official national targets are referenced, they must be clearly distinguished from project KPIs. Figure 2 provides the national waste-diversion context reported under Vision 2030; it should not be interpreted as a construction-project benchmark.

Table 3: Proposed project-level circularity and construction-waste performance indicators

Indicator	Suggested calculation	Interpretation
Waste intensity	Total non-hazardous C&D waste / functional project output	Tracks waste generation independent of project size.
Source-segregation rate	Mass segregated at source / total C&D waste generated $\times 100$	Measures quality of site waste control.
Direct reuse rate	Mass directly reused / total recoverable material generated $\times 100$	Captures higher-value circularity.
Recycling rate	Mass sent to verified recycling / total C&D waste generated $\times 100$	Shows recycling performance but should be read with reuse and prevention.
Landfill diversion	Mass not disposed to landfill / total C&D waste generated $\times 100$	Useful headline indicator; does not show value retention alone.
Recycled-content rate	Mass of verified secondary input / total purchased mass for selected materials $\times 100$	Measures market demand for circular products.
Circular procurement coverage	Relevant contract value with circular clauses / relevant contract value $\times 100$	Shows commercial integration.

Indicator	Suggested calculation	Interpretation
Traceability completeness	Mass with verified origin-destination records / total reported waste mass $\times 100$	Measures data reliability.
Design prevention	Baseline material quantity avoided through approved redesign / baseline quantity $\times 100$	Shows upstream waste/resource prevention.

8. Digitalisation, Material Passports and Traceability

Digital systems can connect design intent, physical material flows and evidence of recovery. BIM provides a natural starting point because it contains geometry, quantities and object information. A circular BIM workflow can add material attributes such as product type, manufacturer, composition, recycled content, expected service life, connection type, potential hazards and preferred end-of-life pathway. At project completion, selected fields can be transferred into asset-management systems or material passports.

Material passports are particularly valuable for future deconstruction because they reduce uncertainty. Honic et al. (2021) demonstrated their ability to support end-of-life recycling assessment, while Atta et al. (2021) linked digital material passports with BIM-based sustainability decisions. Recent research has expanded the information architecture of passports and linked them to disassembly planning and interoperable data standards. The practical lesson for Saudi mega-projects is that complete digital twins are not required for every temporary material; rather, information effort should be proportional to future value and decision need.

For construction waste, digital manifests can record source package, waste type, quantity, transporter, receiving facility and final treatment. QR codes, weighbridge integration or mobile applications can reduce manual transcription. Where recycled outputs are returned to the project, the system can link recovered material certificates to procurement records. This creates an auditable chain from waste generation to circular re-entry.

Digital marketplaces can address another problem: matching supply and demand. Surplus materials or reusable components can be listed with quantity, specification, condition, location and availability date. Larger project portfolios may create internal exchanges before offering materials externally. Such platforms require governance because data must be trustworthy and liabilities clear. Lu et al. (2023) identify information asymmetry as a key obstacle in waste-material trading, which supports the case for standardised material information.

Technology, however, should not replace physical controls. A perfectly recorded mixed-waste load is still a lost circular opportunity. Digital tools are most effective when paired with source segregation, quality assurance and procurement demand. Figure 3 illustrates this combined physical and information loop.

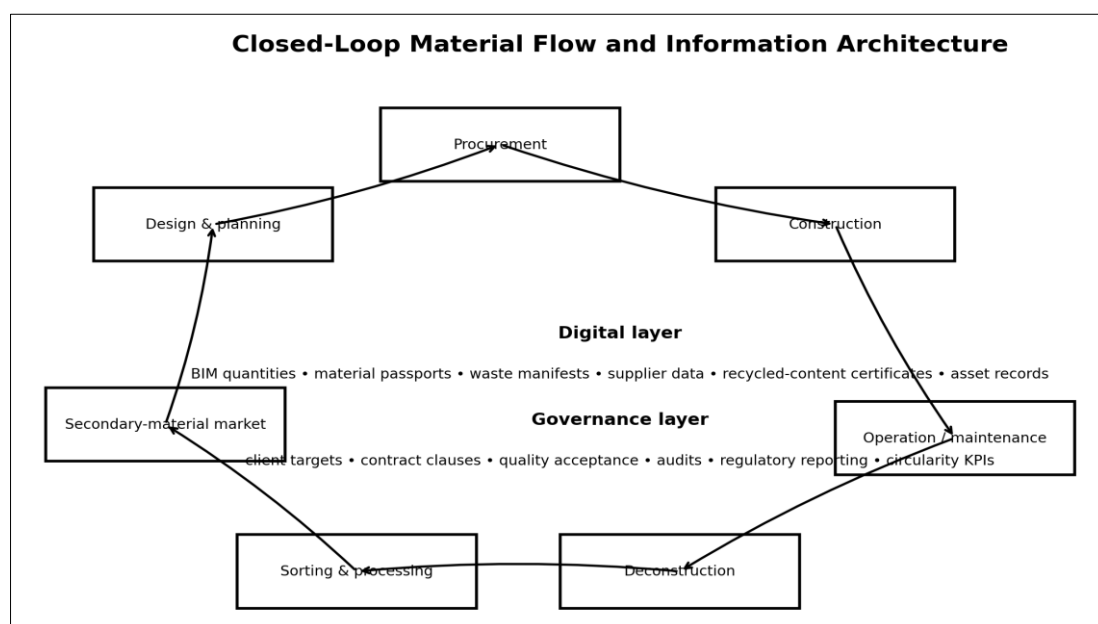


Figure 3: Closed-loop material flow supported by digital information and governance

9. Implementation Roadmap for Saudi Mega-Projects

Implementation should begin at client and program level rather than waiting for individual contractors. The first phase is governance mobilisation. The owner establishes a circular-economy policy, defines minimum waste and material requirements, assigns an accountable executive sponsor and creates a cross-functional working group involving design, procurement, construction, sustainability, commercial and asset-management teams. A baseline assessment identifies likely material flows, local recycling capacity, regulatory requirements and market constraints.

The second phase embeds circularity into design and procurement. Major design packages undergo material-efficiency and circular-design reviews at defined gates. Bills of quantities are used to identify high-impact materials. Specifications are screened for unnecessary barriers to recycled products, while technical teams identify approved applications for secondary materials. Tender documents require waste forecasts, segregation plans, take-back proposals and data reporting. Contractor evaluation considers capability and previous performance.

The third phase operationalises site controls. Before work starts, the contractor establishes segregation zones, signage, containers, logistics routes, training and waste-recording systems. High-volume streams such as excavation material, concrete and asphalt are managed through specific material plans. Opportunities for on-site reuse are evaluated early because storage and programme constraints can eliminate them later. Hazardous

waste remains segregated under dedicated legal and safety controls.

The fourth phase develops recovery and market partnerships. Projects prequalify recycling facilities and suppliers, define quality tests for recovered outputs and negotiate long-term arrangements where volume justifies them. Where multiple packages operate within one development, the client can coordinate surplus-material exchanges and central recovery infrastructure. SIRC and other licensed operators can form part of this ecosystem where geographically and technically appropriate.

The fifth phase is performance optimisation. Dashboards compare actual waste and material performance with forecasts. Repeated contamination, rejected recycled products or low take-up of secondary materials are treated as management problems requiring root-cause analysis. Lessons are fed back to design standards, procurement templates and contractor requirements for subsequent packages. This is how a mega-project becomes a learning system rather than a collection of isolated contracts.

Finally, asset handover preserves circular information. Material passports or structured asset data are retained for major components with future reuse, refurbishment or recycling value. Deconstruction principles and material inventories can form part of long-term asset documentation. This is especially important for rapidly developing Saudi cities because assets built during the current investment cycle will form the material stock of future decades.

Table 4: Barrier-response matrix for implementation at project level

Barrier	Project-level response	Responsible lead	Example evidence
Limited circular awareness	Mandatory role-based training and design/procurement guidance.	Client sustainability + contractor training	Training records; competency checks.
Specification barriers	Technical review of virgin-material-only clauses; approved recycled alternatives.	Engineering + quality	Revised specifications; test reports.
Poor segregation	Stream-specific bins/zones, supervision and contamination KPIs.	Construction manager	Inspection records; contamination rates.
Insufficient outlets	Prequalify recyclers; material exchange; mobile/on-site processing where justified.	Waste/materials manager	Outlet register; contracts; destination evidence.
Weak secondary-material demand	Minimum recycled-content requirements in suitable applications.	Procurement + design	Purchase records; supplier certificates.
Data gaps	Digital manifests and reconciliation with weighbridge/invoice data.	Digital + sustainability	Traceability dashboard.
Schedule mismatch	Material banks and cross-package planning.	Program controls	Inventory and transfer records.
Quality/liability concerns	Defined tests, acceptance criteria and chain of custody.	Engineering + QA/QC	Certificates, approvals and NCR trends.

Table 5: Illustrative three-stage implementation roadmap for a Saudi mega-project programme

Phase	0-6 months	6-18 months	18-36 months
Governance	Policy, roles, baseline, common definitions.	Integrate KPIs into contracts and reviews.	Portfolio benchmarking and continuous improvement.
Design	Pilot circular design reviews.	Mandatory gates for major packages.	Standard circular details/specifications.
Procurement	Identify priority materials and suppliers.	Framework agreements, take-back and recycled-content clauses.	Portfolio demand aggregation and supplier scorecards.
Site delivery	Standard waste plans, segregation and traceability.	Digital dashboards and cross-package material exchange.	Predictive material-flow planning.
Market & recovery	Map licensed outlets and quality requirements.	Long-term recycler partnerships and on-site recovery pilots.	Closed-loop supply agreements.
Data	Define minimum data set.	BIM/passport pilots for high-value materials.	Asset-level circular material registry.

10. DISCUSSION

The proposed framework reframes construction waste as a strategic resource issue. This is particularly relevant to Saudi Arabia because the country is simultaneously building new material-intensive assets and expanding its waste-management infrastructure. If these two systems evolve separately, recycling capacity may grow without stable demand for outputs, while construction projects continue specifying virgin materials. Circular procurement provides the bridge.

Mega-projects have structural advantages for circularity. Their scale allows investment in dedicated recovery infrastructure, digital systems and specialist teams. Their procurement power can stimulate suppliers. Their long programs create opportunities to transfer recovered materials from one package to another. Yet scale also creates governance challenges. Multiple joint ventures, subcontractors and consultants may apply inconsistent definitions and reporting methods. Program-level standards are therefore essential.

The framework also shows why recycling targets alone are insufficient. High diversion is compatible with high material consumption. A project can recycle most waste while generating excessive waste through design changes, rework or over-ordering. Prevention indicators are needed to reveal whether upstream decisions are improving. Similarly, recycled-content procurement is necessary to close the loop; otherwise, recovered materials leave the project without reducing demand for virgin resources.

Saudi-specific implementation should consider geography and market maturity. Remote projects may face long transport distances to recycling facilities, potentially reducing

environmental and economic benefits. In such cases, mobile processing, on-site reuse or temporary material banks may be more appropriate. Urban projects may have better access to established facilities but greater space constraints for segregation. The framework deliberately avoids prescribing one universal recovery method; it requires projects to compare options using technical, environmental, commercial and regulatory criteria.

The emerging ISO 59000 standards can strengthen consistency. ISO 59004:2024 provides a common vocabulary and implementation principles, ISO 59010:2024 focuses on value networks, and ISO 59020:2024 supports circularity measurement. Although revisions to parts of the family are already under development, the published 2024 editions provide a useful current reference for organisations building circular-economy management systems. Saudi mega-projects can use these standards alongside environmental management, quality and project-control systems rather than creating isolated circularity procedures.

There is also a strong research opportunity. Saudi Arabia's mega-project portfolio provides diverse cases across deserts, mountains, coasts, urban districts and industrial zones. Empirical studies can compare waste intensity, recovery pathways, market constraints and digital maturity across sectors. Longitudinal research can assess whether contractual circularity clauses actually change material outcomes. Such evidence would allow the framework proposed here to evolve from a conceptual model into a validated Saudi benchmark system.

11. Research Implications and Future Validation

The proposed framework should be validated in three stages. First, an expert Delphi study can test the completeness and clarity of the lifecycle

stages, barriers, enablers and indicators. Participants should include client sustainability leaders, environmental managers, designers, contractors, recyclers, regulators, procurement specialists and asset operators. Consensus analysis can identify which indicators are practical and which require modification.

Second, the framework should be piloted on at least three different project types, such as urban development, transport infrastructure and industrial or tourism infrastructure. Real material-flow data should be collected from bills of quantities, waste manifests, weighbridges, procurement systems and recovery certificates. This would allow calculation of waste intensity, segregation efficiency, reuse, recycling, secondary-material procurement and data completeness.

Third, outcome evaluation should compare project packages with different levels of circular-economy maturity. Researchers could test whether early design reviews reduce waste intensity, whether contract incentives increase segregation, whether digital traceability reduces reporting gaps and whether recycled-content specifications strengthen local secondary-material demand. Such research would move beyond perception surveys and generate evidence of causal mechanisms.

Future studies should also evaluate environmental trade-offs. Recycling is not automatically beneficial if transport and processing impacts exceed the avoided burden of virgin material. Lifecycle assessment can compare reuse, recycling and disposal routes for major Saudi material streams. Economic analysis can incorporate landfill costs, material purchase savings, logistics, processing, quality testing and residual material value. Social outcomes such as green employment, worker capability and local enterprise development can also be incorporated.

Finally, circular construction research should connect with carbon accounting. Cement, steel and aluminium are major sources of embodied emissions, and circular strategies can reduce demand for primary production. However, material circularity and carbon reduction are related but not identical. A robust Saudi framework should therefore report both circularity and lifecycle carbon indicators rather than assuming one automatically represents the other.

12. CONCLUSION

Saudi Arabia's infrastructure transformation creates both a material challenge and an opportunity. The challenge is that rapid construction can generate large volumes of waste and lock in decades of future

resource demand. The opportunity is that large, coordinated projects can reshape markets by preventing waste, specifying circular products, creating recoverable material streams and generating reliable demand for secondary resources.

This paper develops a Circular Construction and Waste Management Framework tailored to Saudi mega-projects and aligned with the direction of Vision 2030. The framework moves beyond end-of-pipe recycling through six stages: prevention and demand reduction; circular design; circular procurement; source segregation and construction control; recovery and quality assurance; and reintegration into new projects and future asset cycles. Governance, market development, digital traceability and performance measurement operate across all stages.

Recent Saudi studies show that awareness, regulation, education, incentives, technology and market maturity remain central implementation issues. Current national policy and investment are strengthening the enabling environment, including waste-sector regulation and recycling infrastructure. The next step is to ensure that project delivery systems translate these conditions into measurable material outcomes.

For practitioners, the central message is simple: waste management should begin before waste exists. Design determines material demand; procurement determines market signals; construction determines segregation quality; recovery systems determine whether material value is preserved; and asset information determines whether future generations can recover what is built today. When these decisions are linked, Saudi mega-projects can become active instruments of the circular economy rather than merely large generators of recyclable waste.

The framework remains conceptual and should be empirically validated. Future research using real project data, expert consensus and lifecycle assessment can establish Saudi benchmarks and quantify the environmental and economic benefits of different circular strategies. Such evidence can support a transition from isolated good practices to a consistent national model for circular construction under Vision 2030.

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