INDUSTRIAL ENGINEERING AND WASTE MANAGEMENT

Optimizing Old Corrugated Cardboard Recycling Processes to Support Saudi Arabia's Circular Economy under Vision 2030

Mohammed Hasan Alamoudi

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Abstract

Old corrugated cardboard is a potentially valuable secondary fibre resource, but collection volume alone does not establish effective circularity. Its recovery depends on contamination control, consistent feed preparation, selective processing and production of material that meets downstream specifications. This critical narrative review examines how Saudi recycling operations can optimize those connected functions while supporting the circular economy orientation of Vision 2030. Published studies on recycled fibres, refining, material characterization, water management and environmental assessment are combined with official Saudi sector information. The synthesis distinguishes upstream collection and baling from downstream paper-mill operations, avoiding attribution of unverified mill responsibilities to recycling operators. It proposes a framework linking supplier quality, equipment reliability and usable fibre yield with water, energy and product requirements. Published laboratory results illustrate the interaction between nanofibre retention and starch, while an explicitly hypothetical sensitivity graph explains why contamination and processing yield must be evaluated together. Three tables and a process diagram translate the synthesis into operating controls and a validation plan. The analysis favors staged improvement based on measured loss mechanisms over universal equipment prescriptions. Saudi facility trials are needed to establish actual technical, economic and environmental effects; no primary operating results are claimed.

Keywords: circular economy; old corrugated cardboard; recovered fibre; recycling optimization; Saudi Arabia; Vision 2030

1 Introduction

Old corrugated cardboard, commonly classified as old corrugated containers or OCC, connects packaging consumption with secondary fibre production. The material can re-enter containerboard manufacturing when its recovered fibres and contaminants are compatible with the receiving process. Consequently, a recycling operation should evaluate what its customer can use, rather than equating all collected cardboard with usable fibre. Wet, contaminated or incorrectly classified loads may increase purchased mass without increasing accepted output. Process optimization begins with that distinction and continues through sorting, baling, repulping, cleaning and product verification.

Saudi Arabia's circular economy transition provides the strategic context. The National Center for Waste Management describes regulation, investment and service quality through circular economy principles. The Public Investment Fund identifies recovered-paper conversion and local industrial supply chains within its description of MEPCO's role. These official sources establish the relevance of secondary fibre production to national diversification and sustainability. They do not establish the recycling rate of a particular facility or prove a maintenance saving. Operational contributions must be demonstrated through measured material recovery and credible resource accounting.

1.1 Aim and research questions

The aim is to develop an evidence-informed framework for optimizing OCC recovery and processing in Saudi Arabia. Four objectives guide the analysis: identify quality losses across collection and processing; compare fibre-treatment options against resource and product constraints; integrate reliability and procurement with usable yield; and specify an empirical evaluation pathway. The review asks how supplier quality should influence process settings, how refining and cleaning tradeoffs should be assessed, and which measures demonstrate circular performance. The intended contribution is a testable operating framework rather than an unperformed facility experiment.

2 Literature review

2.1 Circular economy and the Saudi context

Saudi Vision 2030 identifies environmental sustainability alongside economic diversification. Kirchherr et al. (2017) explain why circularity requires attention to the wider system rather than recycling alone. Geissdoerfer and colleagues (2017) distinguish circular economy mechanisms from broader sustainability outcomes. Applied to OCC, these perspectives require verification of usable fibre, resource consumption and downstream demand together. A collected tonne cannot demonstrate those outcomes independently.

2.2 Collection, sorting and feed preparation

Source separation is an operational quality control rather than simply a collection preference. Contracts should define accepted OCC, prohibited materials and moisture treatment using specifications agreed with the receiving mill. Loads should retain supplier identifiers so that recurring contamination can be traced. Inspecting a single accessible bale face cannot establish the composition of a heterogeneous delivery. A representative sampling procedure should specify locations, frequency, opening methods and handling of disputed results. These are proposed controls requiring local agreement; no universal acceptance threshold is assumed for Saudi facilities.

Coated and treated corrugated materials need particular attention because visual similarity does not prove compatibility with an OCC recycling stream. The American Forest and Paper Association describes testing protocols for repulpability and recyclability of coated or treated corrugated board. The guidance supports verifying compatibility through appropriate testing, rather than declaring all protective treatments unacceptable or automatically recyclable. A Saudi operator should use the receiving customer's requirements and applicable local obligations. An international voluntary standard should not be presented as Saudi law or as sufficient evidence of product compliance.

Moisture changes the relationship between purchased mass, transport cost and recoverable dry material. Procurement comparisons should therefore use a defined dry-mass basis alongside quality information. Storage protection, inventory rotation and prompt handling reduce avoidable deterioration exposure, but their actual benefit must be measured. Receiving records should distinguish moisture variation from nonpaper contamination because the corrective actions differ. Paying only for gross weight can weaken quality incentives; rejecting every variable load can disrupt supply. A transparent adjustment mechanism can balance these concerns if sampling and dispute resolution are credible.

Sorting and baling create a clear boundary between upstream recovery and papermaking. Collection facilities should optimize segregation, feed consistency, removal of identifiable contaminants and

delivery integrity. Mill operations subsequently determine repulping, screening, fibre treatment and sheet formation. A partnership can link these stages without assuming that one operator controls the entire system. Bale identifiers should survive transfer, allowing downstream complaints to inform upstream decisions. Bale density should follow customer and transport needs while retaining safe handling; higher density alone does not demonstrate better fibre recovery.

Kroell and colleagues review optical sensing and machine learning for material flow characterization. Their work supports investigating measured composition alongside equipment operation. For OCC, automated sensing may assist feed characterization, but obscured materials, variable presentation and local calibration require validation. Manual quality sampling remains relevant. A practical pilot should compare the automated result with independent samples and identify whether it changes supplier or sorting decisions. Installing a sensor without a reliable response process creates data, but does not establish improved recovery or reduced contamination.

Robertson (2021) reviews aseptic beverage cartons, whose multilayer structure differs from ordinary OCC. Their recoverability does not justify mixing them indiscriminately into a corrugated-cardboard stream; acceptance should follow the receiving process and product requirements.

2.3 Repulping, cleaning and fibre treatment

2.3.1 Repulping and separation

Repulping should release usable fibres while enabling removal of incompatible material. Greater mechanical intensity is not automatically optimal: it may change the size of contaminants and influence later separation. Candidate controls include consistency, residence time, temperature and feed sequencing, subject to equipment design and safety procedures. The appropriate operating window should be established through trials on representative OCC mixtures. A low reject mass can be misleading if contaminants remain in accepts. Conversely, a high reject stream may contain recoverable fibre. Both outputs require characterization before engineers change settings.

Screening and cleaning should be evaluated as a network of separation decisions. The plant should measure accepts and rejects on consistent dry-mass boundaries and account for intermediate storage. Fibre loss should be distinguished from removed nonfibrous material. A proposal to reprocess rejects needs an evaluation of recovered value, contamination recirculation, energy and equipment capacity. The preferred arrangement depends on the contaminant population and the receiving product. This review recommends measuring stage performance before purchasing additional equipment, because an apparently weak separation may originate in upstream feed preparation or an incorrect operating setting.

Reynolds and colleagues investigated classification and purification of OCC for dissolving-grade pulp. Their study illustrates how fibre fractions can differ and support tailored processing. Its target differs from conventional recycled containerboard, so its chemical treatment sequence should not be adopted as a standard Saudi OCC recipe. The transferable principle is selective treatment of material fractions. A packaging application would need separate assessment of strength, yield, chemical demand and economics before introducing fractionation. Higher purity does not by itself establish the best use of a recovered feedstock.

2.3.2 Fibre condition and refining

Recycled fibres do not retain identical properties through repeated processing. Sjöstrand and colleagues examined hornification in commercial chemical pulps and its relationship with water

removal. The study offers mechanistic context for changes in swelling and flexibility, rather than an estimate of Saudi OCC degradation. Pătrăucean-Patrașcu and colleagues review chemical and structural transformations in secondary cellulose fibres. Together these sources support evaluating actual fibre condition when selecting treatment. The proposed framework avoids assuming a fixed number of recycling cycles or a universal strength penalty for all recovered cardboard.

Park and colleagues compared ultra-fine and conventional refiner plates for Korean OCC. Their results indicate a tradeoff between throughput and energy efficiency at a targeted fibre-quality outcome. That distinction matters because comparing only specific electricity consumption can favor a process that does not meet the required product specification. A Saudi trial should therefore compare treatments at equivalent quality targets and document feed characteristics. Refiner selection should consider hydraulic capacity, fibre response and the downstream production constraint; one plate configuration cannot be declared universally superior from a single experimental setting.

2.3.3 Additives and product requirements

Jirarotepinyo and Venditti examined refining, cationic starch and OCC-derived nanofibres using a designed experiment. They reported nanofibre retention of 44.8% without cationic starch and 90.0% with it. Figure 1 reproduces those two published values as a contextual comparison. They describe the tested system, not Saudi facility performance or a recommended universal dose. The operational lesson is to evaluate interactions between treatments: additive use, retention and drainage must be considered together before assuming that a stronger laboratory sheet represents a commercially preferable process.

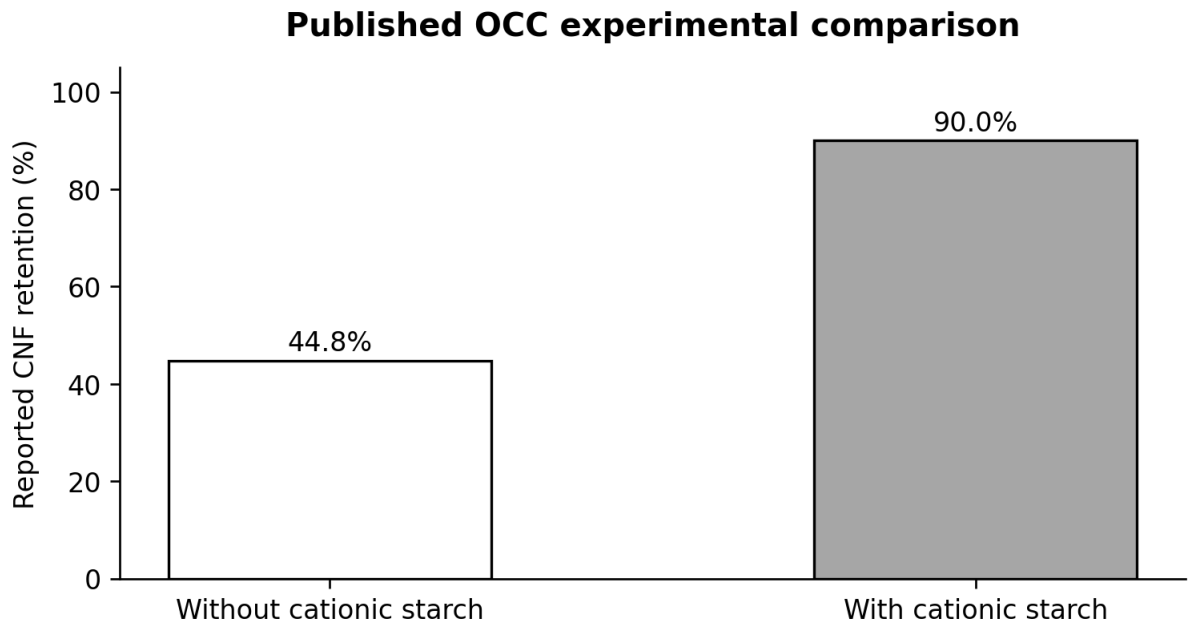


Figure 1. Reported nanofibre retention of 44.8% and 90.0% without and with cationic starch in a published experimental system (not Saudi operating data).

Product requirements should determine the acceptable balance between fibre treatment and resources. Containerboard applications may prioritize compression-related behavior, bonding and specified moisture, while alternative fibre products have different requirements. A receiving mill's grade specification should guide acceptance testing. Chemical or nanofibre additions require

evaluation of preparation energy, retention, cost and process-water effects. This paper proposes starting with feed quality and basic process stability before introducing complex treatments. Advanced additions become more defensible when they resolve a verified quality limitation and outperform a simpler option under comparable conditions.

2.4 Water, energy and environmental performance

Water recirculation can reduce freshwater demand but changes the chemistry and contaminant load seen by equipment and fibres. Hubbe and colleagues review wastewater treatment and reclamation approaches in pulp and paper operations. Their work supports evaluating treatment and process changes together. For an OCC mill, a proposed water strategy should measure intake, recirculated flow, discharge and water quality at relevant points. Closing a circuit more tightly may create operational problems if unwanted constituents accumulate. A reduction in intake is therefore incomplete evidence unless output quality and treatment requirements remain acceptable.

Energy accounting should separate upstream logistics and baling from mill repulping, pumping, refining and drying where those stages are included. The denominator is equally important. Electricity per incoming tonne measures processing intensity, whereas electricity per accepted dry tonne captures yield effects. Thermal energy should remain separately visible. An apparent saving may arise from a changed product grade, wetter input or lower throughput. Comparisons should control these conditions. The proposed dashboard combines energy intensity, accepted output and equipment availability so that one improving ratio cannot conceal losses elsewhere in the system.

Azuaje and colleagues compared allocation methods for environmental assessment of recycled and virgin-fibre containerboard. Their analysis highlights the importance of fibre losses and accounting choices. Accordingly, this paper does not assign a universal carbon saving to each tonne of OCC. Environmental evaluation should specify transport, electricity, water treatment, rejects and the displaced product. Attribution should avoid crediting the same benefit to both collector and mill without explaining the allocation. Sensitivity analysis can show whether a claimed improvement remains credible under different assumptions about downstream substitution and residual-material treatment.

Bradshaw and colleagues show that United States material recovery facilities vary in scale, materials, energy use and market access. Their findings caution against comparing Saudi OCC operators with generic recycling benchmarks without checking system boundaries. A collected tonne, a baled tonne and an accepted fibre tonne are different functional outputs. The proposed approach uses the output relevant to each decision and links stages through a material balance. Circular performance is strongest when compliant secondary material reaches a verified customer; collecting material that remains unused does not complete that chain.

3 Research methodology

3.1 Review design and search strategy

A critical narrative review was conducted using targeted searches of publicly accessible publisher records, institutional repositories and official Saudi sources on 11 October 2026. Search terms combined old corrugated containers, recycling, refining, fibre quality, contamination, hornification, circular economy, water reclamation and Saudi Arabia. Recent research from 2020 to 2025 was prioritized, with earlier methodological literature included where relevant. Direct subscription

database searches of Scopus or Web of Science were not undertaken. This manuscript should therefore be evaluated as a targeted synthesis, without claims of exhaustive coverage.

Snyder (2019) supports matching review design to the research purpose. This synthesis integrates engineering findings and institutional context; it does not present a systematic effectiveness estimate.

3.2 Eligibility and evidence assessment

Included sources addressed OCC processing, recycled-fibre behavior, sorting characterization, environmental accounting or transferable maintenance methods. Official sources were retained for national context and industry guidance was labeled separately from journal evidence. Bibliographic records were checked against publisher or institutional information. Where only abstracts were accessible, conclusions were restricted to their reported scope. Assessment considered the experimental material, laboratory or industrial setting, outcome definitions and transferability. Sources without identifiable methods or publication information were excluded from technical evidence. Table 1 summarizes representative findings and the limits of applying them locally.

3.3 Thematic synthesis and transparency

The sources were organized into feed preparation, fibre treatment, resource management and operational integration themes. No pooled effect size was calculated because outcomes and settings differed. No screening counts or inter-reviewer agreement are invented. PRISMA 2020 offers relevant transparency principles, but this targeted review does not claim completion of a systematic-review protocol. Published measurements are attributed locally, and proposed controls are identified as synthesis. The lack of Saudi primary data limits causal conclusions and makes prospective validation a necessary part of the framework.

Table 1. Selected evidence and transfer limits.

Source	Finding or use	Transfer limit
Park et al.	Refining quality and throughput tradeoffs	Korean OCC; local trials required
Jirarotepinyo and Venditti	Interactions among refining and additives	Experimental conditions are not universal
Sjöstrand et al.	Hornification and water removal	Chemical pulps; mechanistic context
Reynolds et al.	Fraction-specific processing potential	Dissolving pulp differs from containerboard
Hubbe et al.	Water treatment and reclamation	Match treatment to site water quality
Azuaje et al.	Allocation and fibre-loss accounting	Environmental assumptions affect interpretation

Author synthesis; findings retain their original study boundaries

4 Results and discussion

4.1 Proposed integrated optimization framework

Figure 3 presents an original process and feedback framework linking supplier classification, sorting, bale traceability, mill treatment and product verification. Quality feedback moves upstream, while water and reject management remain explicit supporting functions. The diagram describes coordina-

tion across organizations; it does not imply that the research scholar operates every stage. The recommended optimization objective minimizes total cost per accepted dry tonne subject to product specifications, equipment capacity and safety constraints. Its cost boundary includes feed procurement, processing, maintenance, rejected material, transport and resource use, rather than electricity alone.

A simple mass-balance illustration clarifies the relationship between contamination and processing yield. Let M denote incoming dry mass, c its nonfibrous contamination fraction, and y the fraction of remaining fibrous material accepted after processing. Then accepted fibre is M × (1 − c) × y. Figure 2 varies explicitly assumed inputs to show the sensitivity of this relationship. The illustration excludes moisture, ash within the fibrous fraction, additive mass and storage changes. It is an explanatory calculation, not a fitted model, measured Saudi result or guaranteed recovery forecast.

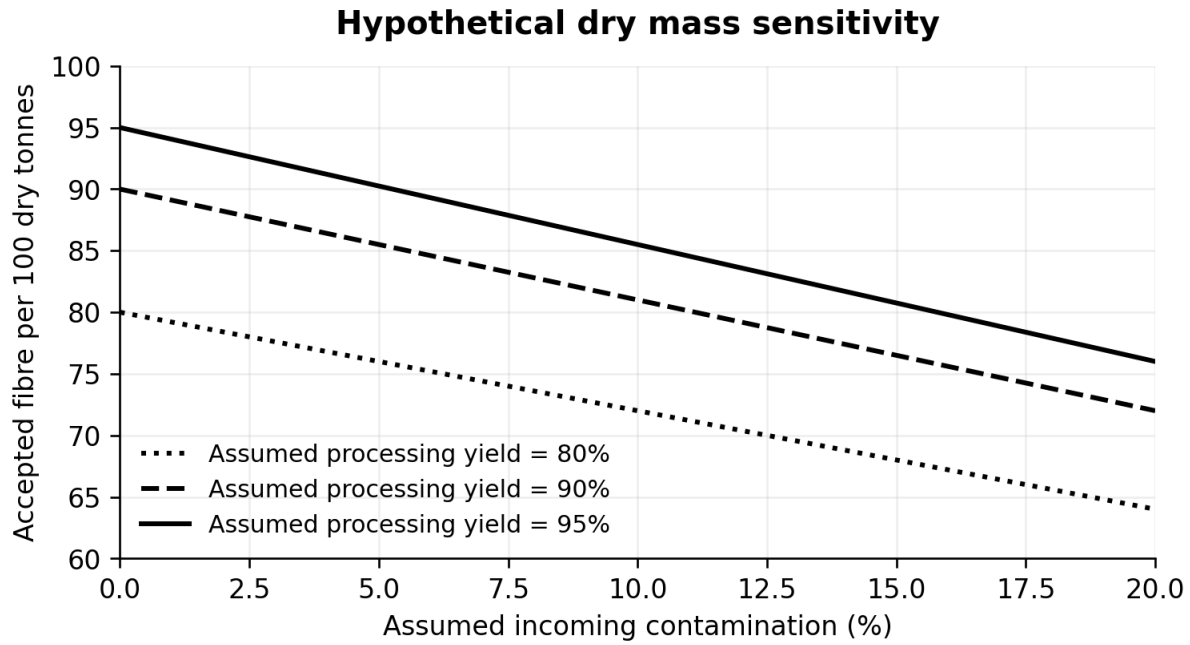


Figure 2. Hypothetical sensitivity calculated as M × (1 − c) × y for M = 100 dry tonnes. Assumed inputs; not observed results.

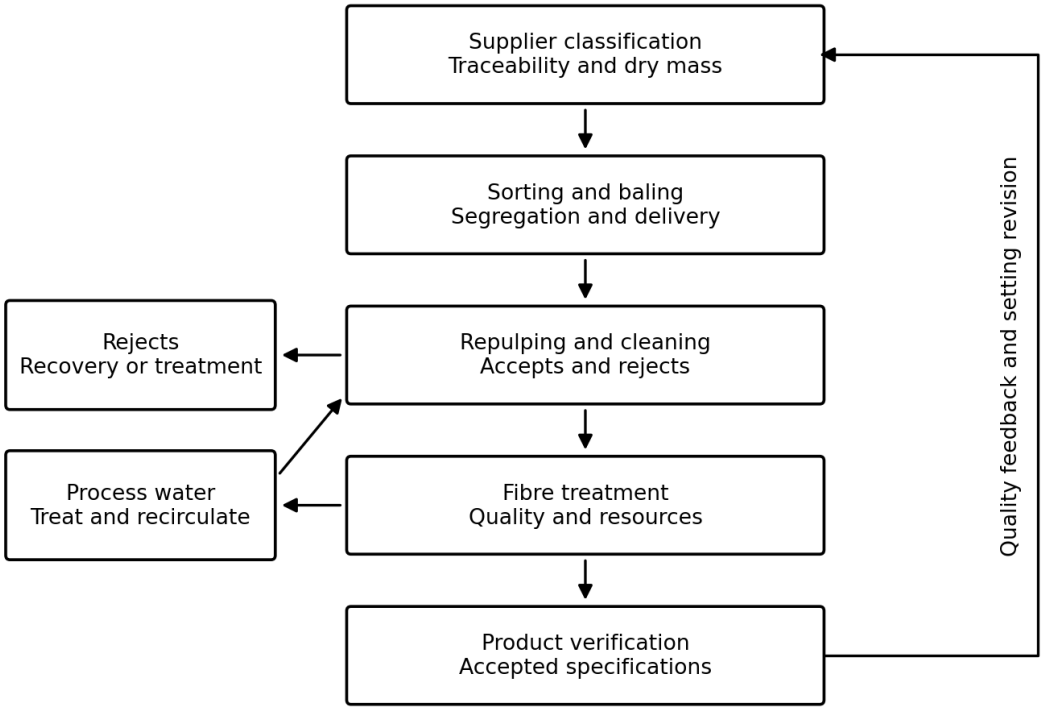


Figure 3. Original proposed OCC process and feedback framework. Arrows describe material progression and supporting relationships; performance requires field validation.

The interaction has practical implications. A facility can increase throughput yet lose value if contamination rises or useful fibres move into rejects. Procurement and production teams should therefore share accepted-yield information. Supplier feedback needs sufficient traceability to separate incoming quality from treatment performance. Table 2 proposes controls at each interface, including the evidence required before claiming improvement. The framework favors a small number of reliable measures over a large dashboard of inconsistent ratios. An apparent gain should be reviewed against sampling uncertainty and the material balance before changing commercial terms.

Table 2. Proposed controls and performance measures.

Interface	Control	Measure
Procurement	Representative supplier sampling	Dry mass and contaminant fraction
Sorting and baling	Segregation and bale identifiers	Customer acceptance and sorting losses
Repulping	Representative operating trials	Usable fibre and reject composition
Refining	Compare at matched quality	Energy, strength and drainage
Water	Monitor reuse and treatment	Intake, discharge and relevant water quality
Maintenance	Inspect bottlenecks; verify restoration	Downtime and repeated quality defects
Product release	Apply agreed specification	Accepted yield and off-specification output

Proposed measures; acceptance limits require customer agreement and site validation.

Maintenance supports this framework through dependable material handling and stable treatment. De Jonge and Scarf's review of maintenance optimization emphasizes equipment dependencies. For an OCC operation, this motivates attention to bottleneck conveyors, balers, pumps and utilities rather than ranking machines only by purchase price. Maintenance priorities should also include defects that degrade quality without stopping production. However, predictive technologies require usable condition and event records. Initial work should establish equipment identifiers, repeatable inspections and restoration checks before attempting complex remaining-life prediction or asserting savings from digitalization.

4.2 Implementation and validation

Implementation should begin with an agreed boundary between the recovery operator and receiving mill. Both parties should define the dry-mass basis, accepted grades, sampling method and responsibilities for quality disputes. The baseline should record feed source, moisture, contaminants, processed mass, accepted output and delays. Table 3 proposes staged evidence gates. Equipment upgrades or chemical changes should follow diagnosis of the dominant loss mechanism. A fixed national recipe is inappropriate because feed quality, product requirements and installed equipment differ. Improvement targets should be negotiated from observed baselines and technical feasibility.

Table 3. Proposed implementation and validation sequence.

Stage	Action	Evidence gate
Baseline	Agree boundaries and record flows	Reconciled dry mass and samples
Diagnose	Identify dominant loss mechanism	Feed and equipment explanations separated
Pilot	Test a focused intervention	Safe execution and comparable controls
Evaluate	Assess yield, quality and resources	Uncertainty and total costs reported
Scale	Extend effective changes	Representative operating benefit demonstrated
Review	Track feed and product changes	Settings and specifications revised

Evidence gates replace assumed completion dates or guaranteed savings.

A prospective trial should compare intervention and baseline periods while recording feed and product differences. A comparable untreated line or staggered implementation can strengthen attribution when feasible. Planned analyses should distinguish supplier-quality improvement from treatment changes and maintenance recovery. Primary outcomes should be defined beforehand, with uncertainty reported for yield, quality and resource intensity. A short trial using unusually clean feed cannot establish annual performance. Seasonality, production campaigns and inventory movements require sufficient observation coverage. The study should report unsuccessful settings as well as successful ones to reduce selective interpretation.

Experimental design can assess treatment interactions more efficiently than changing one parameter without a structured comparison. Candidate factors include feed grade, refining intensity and an approved additive level. The design must respect safe operating limits and equipment instructions. Laboratory screening can narrow choices, followed by controlled mill validation. Trials should include drainage and resource outcomes alongside strength. Commercial assessment needs actual delivered input costs, residual treatment costs and accepted product value. The economic outcome should not be inferred solely from a laboratory percentage improvement or an equipment supplier's projected saving.

4.3 Measurement quality

Comparable trials require explicit test methods. ISO 638-1:2022 covers oven-dry matter determination for solid paper-related materials. ISO 5267-1:1999 provides the Schopper-Riegler drainability method. ISO 1924-2:2008 addresses tensile testing of paper and board, including corrugated-board components rather than assembled corrugated board. ISO 187:2022 addresses conditioning and testing atmospheres. These standards guide measurement selection; they do not establish customer acceptance limits or prove that the proposed intervention is effective.

Hubbe et al. (2007) distinguish fibre-related changes from contamination effects during recycling. Hubbe (2014) evaluates interacting strategies for retaining paper strength with fewer forest resources. Together, these reviews support evaluating feed history, bonding and processing as connected variables rather than selecting one universal treatment.

4.4 Managerial implications and research gaps

The synthesis favors optimization of usable fibre over optimization of collection volume. It also shows why upstream quality decisions and downstream treatment cannot be assessed independently. Better segregation can alter the operating window, while stronger treatment can change rejects, drainage and resource demand. The proposed contribution is a framework that connects these relationships through traceable material balances and shared quality criteria. Its effectiveness remains untested. Saudi studies should compare source-separated commercial OCC with more heterogeneous recovered streams and evaluate whether additional sorting costs are offset by accepted-yield and operating benefits.

5 Conclusion and recommendations

Saudi OCC recycling should be optimized through coordinated feed-quality control, selective processing, equipment reliability and verification of accepted secondary fibre. Published research supports evaluating treatment interactions and balancing strength with drainage, yield and resource demand. The proposed framework connects upstream recovery with receiving-mill requirements while keeping responsibilities explicit. Its implementation should begin with traceable samples and dependable mass balances, followed by focused trials and economic evaluation. Actual benefits must be demonstrated under representative Saudi conditions. This approach provides a practical research pathway for improving circular material use in support of Vision 2030.

6 Future directions

This review relies on targeted searching and includes sources accessible only through abstracts or publication summaries. It is not exhaustive and does not establish a pooled effect estimate. No Saudi facility measurements were supplied, and the proposed framework has not been field validated. International OCC studies may not represent local feedstock or operating conditions. Figure 1 reports a published experimental comparison; Figure 2 is explicitly hypothetical. Official sources provide context rather than technical proof. These limits require cautious transfer and prospective evaluation before making plant-specific savings or environmental claims.

7 Submission declarations

Affiliation and corresponding-author contact require confirmation. Funding, competing interests and author contributions require accurate author statements. No primary facility data were collected. Published measurements and hypothetical calculations are identified separately. AI assisted drafting and figure preparation; authors must verify the manuscript and follow the selected journal disclosure policy.

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