Maintenance Optimization for Municipal Solid Waste Sorting and Recycling Facilities in Saudi Arabia: Improving Reliability and Operational Efficiency.

Abstract

Municipal solid waste sorting and recycling facilities convert discarded materials into secondary resources, but their contribution depends on dependable processing rather than installed capacity alone. This review examines how maintenance optimization can improve reliability and operational efficiency in Saudi Arabian facilities while supporting resource recovery objectives associated with Vision 2030. A targeted synthesis of published maintenance research, recycling studies and official Saudi policy information connects equipment deterioration with material flow, recovered-product quality and organizational readiness. The evidence supports combining asset criticality assessment, preventive maintenance, condition monitoring and coordinated production scheduling instead of applying one maintenance policy throughout a plant. The paper proposes a framework in which safety constraints, bottleneck exposure, spare-parts availability and quality losses govern intervention priorities. It distinguishes published environmental findings from analytical illustrations and does not present either as measured Saudi maintenance outcomes. Three tables translate the synthesis into equipment decisions, performance measures and an implementation sequence. Two graphs and a conceptual diagram clarify analytical relationships and the proposed decision logic. The central contribution is a maintenance model that evaluates saleable recovery alongside availability, allowing managers to recognize technically running equipment that nevertheless produces avoidable rejects. Implementation should begin with reliable work-order and downtime records before adopting complex predictive models. Prospective, controlled studies across Saudi facilities are needed to determine actual effects on downtime, recovery quality, energy intensity and lifecycle cost.

Keywords: municipal solid waste; maintenance optimization; material recovery facility; equipment reliability; Saudi Arabia; circular economy; condition monitoring

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1. Introduction

A recycling facility can meet its mechanical operating schedule while failing to deliver its intended material recovery. Conveyors may continue moving despite unstable feed distribution, a screen may rotate with obstructed openings, and an optical sorter may classify objects while its air supply prevents effective ejection. These situations expose a limitation in maintenance programs centered exclusively on equipment failure. For municipal solid waste facilities, dependable operation must also preserve separation quality, downstream capacity and safe working conditions. Maintenance optimization therefore requires a process perspective that connects machine condition with the quantity and quality of secondary materials leaving the facility.

Saudi Arabia provides an important setting for this question because waste-sector development is explicitly linked to circular economy objectives. The National Center for Waste Management describes its mandate in terms of regulating waste activities, encouraging investment and improving sector quality through circular economy principles. An official government news report also links waste-sector development with Vision 2030. These sources establish policy relevance; they do not demonstrate that a particular maintenance intervention will achieve a national recycling target. Translating strategic ambition into operational performance requires facility-level evidence about why material is lost, which equipment constrains recovery and how maintenance resources are assigned.

1.1 Aim and Research Questions

The aim is to develop an evidence-informed maintenance optimization framework for Saudi municipal solid waste sorting and recycling facilities. Five objectives guide the analysis: identify maintenance-sensitive recovery losses; compare maintenance policies against equipment criticality and operating conditions; connect reliability metrics with product quality and resource intensity; specify the information and organizational capabilities needed for implementation; and define a credible empirical validation pathway. These objectives focus on operational decisions that can be examined with facility records, avoiding assumptions that national policy alignment alone establishes technical effectiveness.

Three research questions organize the review. First, how should equipment and failure modes be prioritized when their consequences include safety exposure, interrupted material flow and degraded separation quality? Second, under what conditions should preventive, condition-based or predictive maintenance replace corrective intervention? Third, how can facilities evaluate improvements while accounting for feed composition, production schedules and differences between installed and usable capacity? The proposed answers are conditional engineering recommendations. They are not estimates of the performance of a named Saudi company, project or plant.

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2. Literature Review

2.1 Sorting Systems and Functional Reliability

A sorting plant behaves as an interconnected flow system. The consequence of a failed conveyor depends on whether material can bypass it, accumulate safely or move through a parallel route. Likewise, a downstream baler may become the effective bottleneck even when separation equipment remains available. Production planning should therefore identify functional dependencies rather than rank assets only by purchase price. A relatively inexpensive transfer conveyor can interrupt the entire line, whereas an expensive unit with usable redundancy may allow continued recovery. The relevant criticality is the consequence of lost function under the actual operating configuration.

Optical classification and mechanical execution are distinct functions. Correctly identifying an object does not guarantee that it reaches the intended output stream. Separation can depend on timing, conveyor presentation and the condition of actuating equipment. Consequently, the maintenance boundary should include supporting compressed air, electrical supply and control interfaces wherever they are necessary for the installed sorter. Utility defects can create systematic quality losses without causing a visible breakdown. Quality-sensitive inspections should therefore verify the delivered separation function using an agreed test procedure, rather than closing work orders solely because an alarm disappears.

Cimpan and colleagues (2015) connect central sorting technology with operational practice and recovered-material quality. Lubongo and Alexandridis (2022) identify limitations when automated equipment encounters difficult plastic combinations and presentation. These findings support diagnosing the feed and the machine together. Maintenance cannot correct a separation task outside the equipment’s design capability.

2.2 Maintenance Policy Selection

Asset criticality should begin with safety and environmental consequences, followed by recovery loss, operational dependency and restoration difficulty. Safety-critical functions require their appropriate protection and inspection arrangements even when their failure is infrequent. For production assets, engineers should identify whether deterioration produces a gradual warning, abrupt damage or progressive quality loss. A failure-mode register can then connect each mechanism to detection opportunities and feasible interventions. Table 2 illustrates this logic for typical equipment groups; it is a proposed decision matrix and does not describe observed failure rates in Saudi plants.

Preventive maintenance remains appropriate where manufacturers specify necessary servicing, deterioration is related to usage or inspection can identify a developing defect economically. Initial intervals should draw on equipment instructions and operating experience, then be revised using observed condition and failure history. Calendar schedules alone may overlook differences in processed tonnage, abrasive exposure or loading. Where possible, facilities should compare calendar age with operating hours and throughput. Extending an interval requires evidence that condition remains acceptable; shortening it should address a documented mechanism rather than simply respond to a general desire for more maintenance.

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Condition-based maintenance links intervention to observed deterioration. Jardine and colleagues distinguish the information acquisition, processing and decision components of that process. For the proposed application, each measurement needs a defined location, operating context and response rule. Vibration can support rotating-equipment diagnosis, temperature can identify abnormal thermal behavior, and oil analysis can inform lubrication decisions where technically appropriate. These examples are candidate methods, not prescriptions for every asset. Monitoring is useful only if the selected signal provides actionable information before the consequences of failure become unacceptable.

ISO 55000:2024 links asset management to organizational value, while ISO 55001:2024 specifies management-system requirements. ISO 31000:2018 provides risk-management guidance. These sources support accountable asset decisions; using them as conceptual guidance does not establish certification or compliance at a facility. ISO 17359:2018 offers a general basis for organizing machine condition monitoring.

2.3 Predictive Maintenance and Decision Support

Carvalho and colleagues review machine learning methods for predictive maintenance, while Zonta and colleagues examine predictive maintenance within Industry 4.0. Together they establish a broad methodological foundation rather than a guaranteed recycling performance improvement. For a waste facility, a prediction should be evaluated against the intervention it enables. A highly accurate classifier may deliver little value if spare parts arrive after failure, while a simpler warning may be useful when it provides enough time for inspection. Lead time, false alarms and missed deterioration therefore matter alongside conventional accuracy measures.

Carvalho and colleagues (2019), Zonta and colleagues (2020), and Esteban and colleagues (2022) synthesize predictive-maintenance methods. Their differing scope reinforces the need to choose models against a stated plant decision rather than adopt analytics solely because they are available.

Jardine, Lin and Banjevic (2006) connect monitoring with maintenance decisions. Esteban and colleagues (2022), Achouch and colleagues (2022), and van Dinter and colleagues (2022) address analytical maturity and implementation. De Jonge and Scarf (2020) explain why dependencies among assets matter. Kroell and colleagues (2022) provide complementary methods for characterizing the recycling feed.

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3. Research Methodology

3.1 Review Design and Source Selection

This manuscript uses a critical narrative review with a transparent targeted search and an engineering synthesis. Publicly accessible publisher pages, institutional repositories and official Saudi sources were consulted on 11 October 2026. Search combinations included municipal solid waste and maintenance; material recovery facility and operations; recycling and optical sorting; predictive maintenance and systematic review; condition monitoring and maintenance optimization; and Saudi Arabia and circular economy. Searches sought recent work from 2020 to 2025, complemented by earlier foundational maintenance research. Direct subscription searches of Scopus and Web of Science were not performed and are not claimed.

Sources were included when they explained a relevant maintenance mechanism, characterized recycling operations, assessed Saudi waste-management alternatives or documented national policy context. Maintenance studies from other industries were retained only as transferable methodological evidence. Advertising pages, unverified performance claims and sources without identifiable publication information were excluded from the scholarly synthesis. Official policy material was retained separately from journal research. Bibliographic information and identifiers were checked against publisher or institutional records. An identifiable DOI confirms a publication record; it does not by itself establish current database indexing, methodological strength or applicability to Saudi recycling equipment.

Snyder (2019) informs the choice of a targeted integrative synthesis. PRISMA 2020, reported by Page and colleagues (2021), supplies transparency principles but this paper does not claim exhaustive systematic screening. Publisher records and official sources were checked; unavailable full texts restricted interpretation to accessible findings. No screening totals or facility experiments are invented.

3.2 Synthesis and Transfer Assessment

Assessment considered source type, study setting, availability of methods, relevance of the asset or process, and whether the reported outcome was measured or modeled. Where only abstracts or publication summaries were accessible, interpretation remained at that level. Detailed experimental procedures and unreported maintenance effects were not inferred. Sources were organized into maintenance policy, monitoring and analytics, sorting performance, environmental context and implementation themes. Disagreements and transferability limitations were considered explicitly. Transfer limits were retained in the synthesis rather than treating different equipment settings as equivalent.

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4. Results and Discussion

4.1 Reliability and Recovery Measures

Maintenance performance requires definitions that remain stable across reporting periods. Mean time between failures should use operating exposure and a clearly defined functional-failure event. Mean time to repair should distinguish active repair from waiting for parts, permissions or specialist support. Operational availability can be calculated directly from the time record, while steady-state intrinsic availability uses simplifying assumptions about repairable equipment. Confusing these measures hides organizational delays. Table 1 recommends a compact set of complementary indicators so that improved repair execution does not mask increasing downtime caused by logistics or poor planning.

For a simple repairable unit, an analytical relationship is A = MTBF / (MTBF + MTTR). Here A denotes intrinsic steady-state availability, MTBF is mean operating time between failures, and MTTR is mean active repair time. The relationship excludes scheduled maintenance and external delays and should not be presented as the measured availability of a full recycling plant. Figure 1 explores its sensitivity using explicit assumed inputs. Its purpose is to explain why repair duration and failure frequency both matter; it cannot predict a Saudi facility's improvement without observed event data and an appropriate system model.

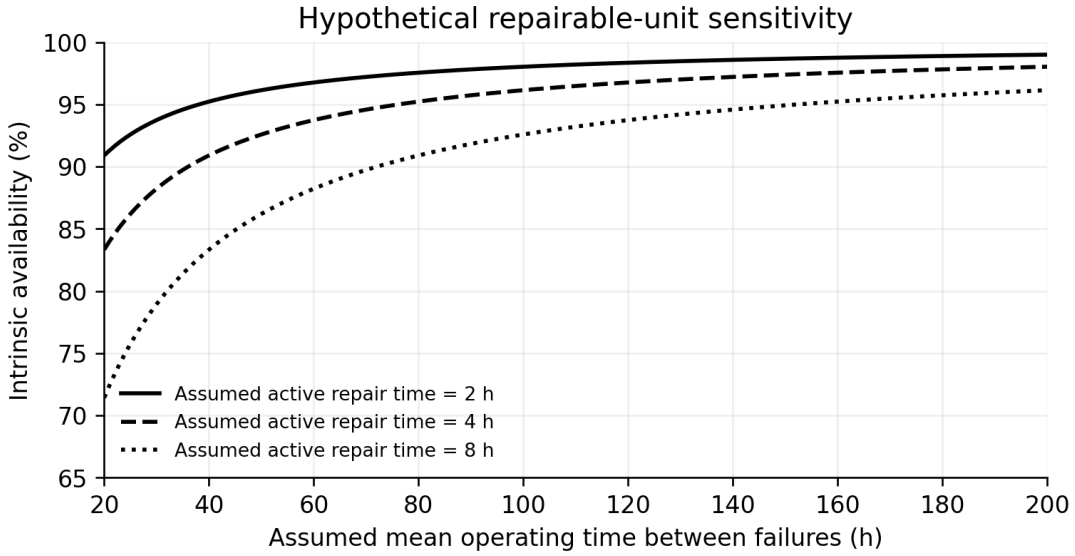


Figure 1 Intrinsic availability calculated as A = MTBF / (MTBF + MTTR). All inputs are assumed; scheduled stops, logistics delays and plant dependencies are excluded.

A maintenance intervention should be evaluated against saleable recovery rather than gross collected mass alone. Increasing belt speed may raise processed tonnage while lowering separation efficiency; maintaining uptime through a bypass can increase downstream rejects. A useful assessment therefore combines feed mass, material-specific recovered mass, purity and rejected output. Material balances should define moisture treatment and record storage changes so that differences in reporting periods do not create artificial recovery gains. The proposed framework requires laboratory or agreed quality checks when sales specifications depend on material composition, with sampling frequency matched to process variability.

Bradshaw and colleagues (2025) demonstrate why facility scale and material composition affect operating comparisons. Energy should be reported per tonne of feed and per tonne of accepted recovery at comparable loading.

Table 1 Proposed performance indicators and interpretation

Indicator	Definition or calculation	Interpretation and caution
Operational availability	Actual running time / defined scheduled production time	Report exclusions and downtime categories; derive from time records
MTBF	Operating exposure / functional-failure count	Define failure and exposure; report uncertainty when events are sparse
Active MTTR	Total active repair hours / completed repairs	Separate waiting, isolation and logistics delays
Saleable recovery yield	Accepted recovered dry mass / incoming dry feed mass	Material mix affects achievable yield; report by material
Recovered-material purity	Target-material mass / sampled output mass	Use a documented, representative sampling method
Energy intensity	Electricity / feed mass and electricity / saleable recovery mass	Keep boundaries consistent; record diesel separately
Maintenance cost intensity	Defined maintenance cost / processed feed mass	Include outsourced work and inventory policy consistently
Repeat intervention rate	Repeat work for the defined same fault / completed repairs	Predefine fault identity and observation window
Alert usefulness	Confirmed actionable alerts / reviewed alerts	Also report missed events, lead time and review workload

Author-proposed reporting set. All ratios require consistent periods, units, boundaries and treatment of missing data.

Aldhafeeri and Alhazmi (2022) and Almansour and Akrami (2024) examine Riyadh waste-management configurations through environmental assessment. They establish the importance of recovery pathways, not the effect of a maintenance intervention. Saudi Vision 2030 and the Saudi Press Agency's sector report supply strategic context. Kirchherr and colleagues (2017) additionally caution against reducing circularity to recycling alone. Actual maintenance benefits require measured output quality and resource use.

4.2 Proposed Optimization Framework

Figure 3 presents an original decision framework built from the preceding synthesis. It begins with a verified asset register and linked information on operating condition, feed characteristics and output quality. A criticality assessment determines which functions require mandatory protection and which production losses justify further analysis. Engineers then select preventive, condition-based or predictive intervention according to deterioration behavior and information quality. The framework explicitly connects a decision to work execution and post-maintenance

verification. That feedback is essential because scheduling a task does not demonstrate restored equipment function or an improvement in recovered-material quality.

The proposed economic objective minimizes expected total operational loss over the planning horizon. Its components include planned maintenance, corrective repair, downtime, degraded product quality, energy consumption, inventory holding and monitoring costs. Safety and environmental obligations operate as constraints rather than losses that can always be traded against production revenue. This formulation prevents the cheapest immediate repair from being mistaken for the best lifecycle decision. It also discourages installing sensors where their expected decision value is lower than their acquisition, maintenance and interpretation costs. Parameters should come from site evidence rather than assumed industry-wide savings percentages.

Bousdekis and colleagues (2021) connect data-driven maintenance decisions with feasible intervention. Warnings should specify the suspected fault, available lead time, required resources and decision owner.

Figure 2 illustrates the joint dependence of accepted output on availability and accepted-output fraction, with rate and scheduled hours held constant. Its normalized percentages are calculated from assumed inputs. The relationship clarifies why improved uptime alone cannot establish higher usable recovery when quality deteriorates.

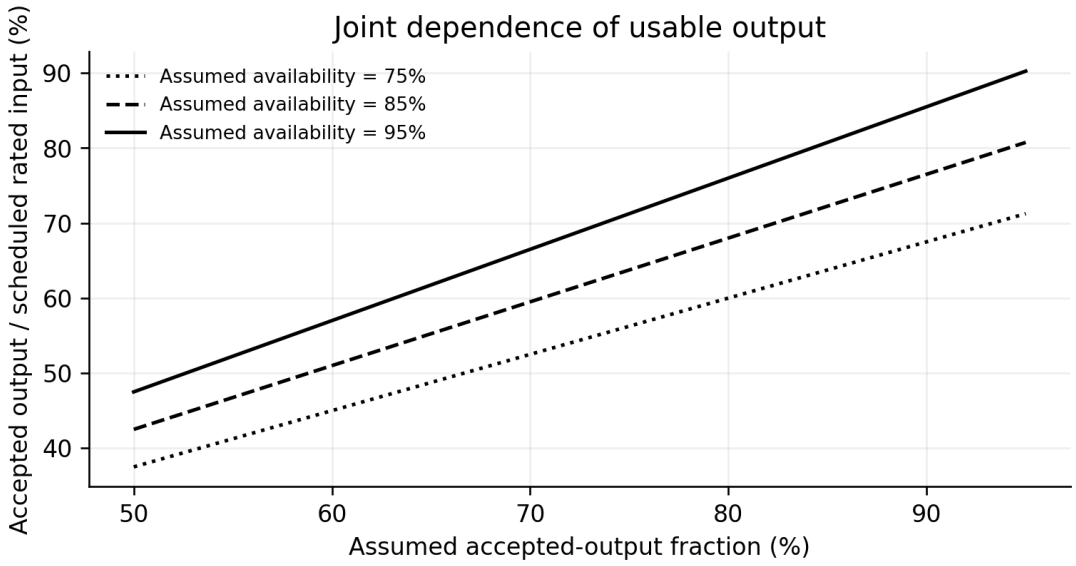
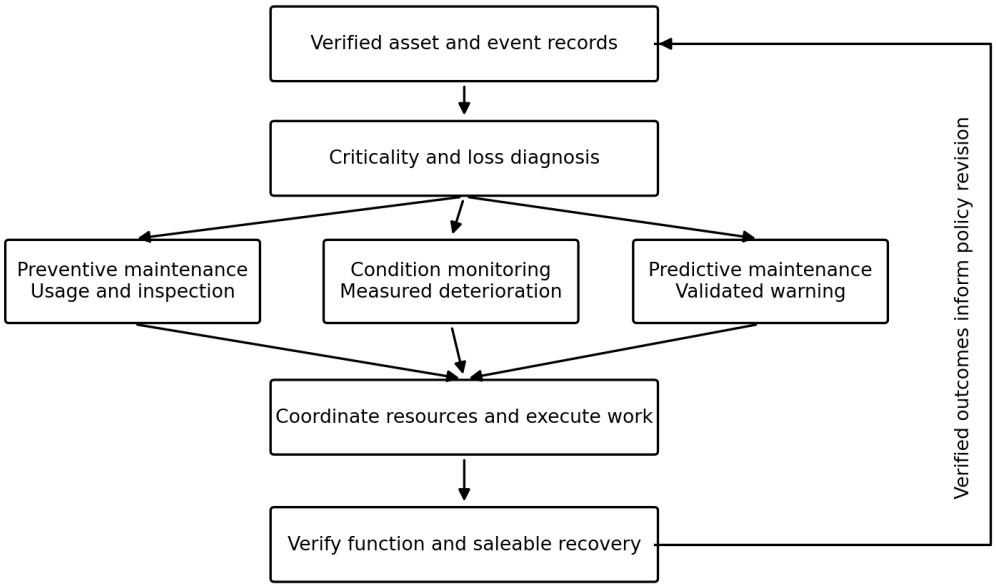


Figure 2 Hypothetical accepted output calculated as availability × accepted-output fraction × scheduled rated input. Constant rate and hours are assumed; no observed plant improvement is reported.

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256 **Figure 3 Original proposed maintenance decision framework. Arrows represent engineering dependencies**
257 **and feedback, not validated causal effects.**

258 **Table 2 Proposed equipment and maintenance decision matrix**

Equipment	Candidate loss or failure mode	Candidate checks	Policy and release criterion
Feeders and conveyors	Blockage, misalignment, drive deterioration; flow interruption	Tracking, loading, drive condition and transfer inspections	Preventive and condition based; stable safe transfer at agreed load
Screens and trommels	Obstruction or wear; misplaced fractions	Opening condition, buildup, drive condition and fraction samples	Cleaning and inspection; verify sizing performance
Magnetic and eddy current units	Poor separation or component deterioration	Installed-unit inspections and output quality checks	OEM servicing plus condition checks; verify relevant metal recovery
Optical sorters	Dirty sensing surfaces, calibration or ejection defects	Reference checks, feed presentation and utility verification	Preventive servicing plus quality-triggered diagnosis; verify purity
Balers	Hydraulic or mechanical deterioration; storage congestion	Leaks, pressure behavior and bale checks under OEM procedure	Preventive and condition based; verify safe bale formation
Compressed air and utilities	Delivery instability; ineffective actuating function	Delivered pressure, leak checks and protective-system tests	Criticality-dependent policy; verify supported process function
Safety functions	Loss of required protective function	Authorized inspection and functional test	Mandatory protection requirements; authorized release only

Proposed engineering matrix, not measured failure data. Final procedures and thresholds require OEM instructions, site risk assessment and qualified engineering approval.

4.3 Information Governance and Execution

Data governance begins with consistent asset and event definitions. The computerized maintenance management system should link each work order to equipment, failure symptoms, verified cause where known, actions, parts and timestamps. Unknown causes should remain explicitly unknown. Operators need a short reporting structure that distinguishes blockage, equipment malfunction, quality deviation and planned stoppage. Maintenance technicians should be able to revise an initial fault classification after inspection without erasing the original report. This preserves the diagnostic history and reduces the risk that convenient administrative categories distort the reliability analysis.

ISO 14224:2016 concerns petroleum, petrochemical and natural-gas equipment. Its separation of equipment, failure and maintenance records is useful methodological inspiration, but a recycling taxonomy requires independent adaptation. The paper does not present this sector standard as a mandatory waste-facility requirement.

4.4 Implementation and Validation

Table 3 proposes a sequence with evidence gates rather than fixed universal deadlines. The first stage establishes the asset register, event definitions and baseline measures. The second tests equipment criticality and corrects recurring defects using inspection and failure analysis. The third pilots condition monitoring on a small number of production-critical assets with plausible deterioration signals. Wider deployment follows only when the pilot demonstrates usable warning, feasible action and acceptable monitoring burden. Scheduling commitments should depend on plant staffing, access and production constraints; the table does not promise a predetermined completion date or percentage saving.

Table 3 Proposed implementation sequence with evidence gates

Stage	Main actions	Evidence gate	Accountability
Baseline	Create asset register; define events; link feed and quality records	Reconciled timestamps and usable reporting coverage	Maintenance and operations leads
Prioritize	Assess safety, dependencies, quality losses and recurring defects	Documented priorities and approved inspection procedures	Engineering with safety and production
Pilot	Monitor selected critical assets; define alerts and response ownership	Actionable signals and recorded response outcomes	Technicians and condition specialist
Evaluate	Compare operational and quality outcomes with suitable controls	Uncertainty, confounders and total costs reported	Analyst with plant engineering
Scale	Extend effective practices; coordinate shutdowns and spares	Demonstrated decision value and feasible resources	Plant management
Review	Reassess policies after feed, equipment or staffing changes	Verified restoration and updated maintenance rules	Cross-functional review team

Proposed sequence. No universal timeframe or guaranteed improvement is assumed.

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A prospective facility study should establish a baseline before intervention, retaining enough operating coverage to characterize relevant feed and seasonal changes. The preferred comparison uses a similar untreated line or a staggered rollout when feasible. Outcomes should include unplanned downtime, saleable recovery, purity, maintenance cost and energy intensity. The analysis must record feed composition, incoming volume, staffing, operating hours and major equipment changes. Without these variables, a throughput improvement caused by cleaner feed or additional shifts could be incorrectly credited to maintenance optimization. Random assignment is desirable where operationally feasible but is not assumed.

4.5 Managerial Implications

The synthesis indicates that maintenance optimization in recycling should be organized around functional recovery. This differs from an asset-only view because output quality can decline before mechanical stoppage, and utility failures can affect separation without interrupting material movement. A facility should therefore couple reliability analysis with material-flow and quality records. The proposed contribution is this explicit connection between maintenance priority, production dependencies and saleable recovery. It remains a conceptual contribution until prospective facility evidence establishes whether the framework improves decisions relative to existing practices under comparable conditions.

For managers, the immediate implication is to fund reliable records, safe access and basic defect elimination before scaling advanced analytics. For project teams, maintenance access and quality verification should be addressed during design and commissioning. For policymakers and sector institutions, consistent reporting definitions could improve comparisons across facilities, while recognizing different feed streams and plant configurations. Linking support to measured recovery and safe operational performance would be more informative than tracking installed capacity alone. These recommendations align with the operational needs of circular resource recovery; they do not imply eligibility or approval under any residency or funding program.

5. Conclusion and Recommendations

Maintenance optimization for Saudi municipal solid waste sorting and recycling facilities should connect equipment reliability with material quality, process bottlenecks and feasible work execution. The literature supports a differentiated mix of preventive maintenance, condition-based intervention and carefully validated predictive methods. The proposed framework adds saleable recovery and resource intensity to conventional downtime analysis, while treating safety as a binding requirement. Implementation should progress through verified baseline records, criticality assessment, focused pilots and controlled evaluation. A prospective Saudi facility study is the necessary next step to establish actual benefits and costs and to determine whether the framework supports more dependable circular-economy operations.

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6. Future Directions

This review is limited by targeted searching, partial reliance on accessible abstracts and the absence of primary Saudi facility data. It is not an exhaustive systematic review, and the evidence does not support a pooled maintenance effect size. Transfer from manufacturing research may be restricted by heterogeneous feed, environmental exposure and differing equipment arrangements. The framework has not been field validated. The availability graph assumes one repairable unit. The accepted-output graph assumes constant rate and scheduled time. Both are illustrations rather than observed maintenance outcomes. These boundaries restrict causal claims while identifying a practical empirical research agenda.

Three research gaps follow. Saudi studies are needed that measure maintenance interventions directly rather than infer operational benefits from national strategy or environmental scenario analysis. Comparative work should distinguish mixed municipal sorting, source-separated recycling and dedicated cardboard facilities. Research should also evaluate whether feed-aware condition models improve decisions over simpler load-adjusted inspection thresholds. These questions call for transparent operating datasets with anonymized asset and event information. Commercial confidentiality can be protected through aggregation, but reporting must retain enough detail for readers to assess equipment boundaries, intervention timing and alternative explanations for observed change.

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