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# The Impact of Packaging Design on Recycling Efficiency in Municipal Systems

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## Abstract

The rapid growth of consumer packaging has placed significant pressure on municipal solid waste management and recycling systems worldwide. While recycling technologies and policies have advanced, recycling efficiency remains constrained by upstream factors, particularly packaging design choices made during product development. This study investigates the impact of packaging design characteristics such as material composition, color, labeling, size, and structural complexity on recycling efficiency within municipal recycling systems. Using a systems-engineering perspective, the research analyzes how design decisions influence material recovery rates, contamination levels, sorting accuracy, and operational costs in material recovery facilities (MRFs). A mixed-method approach combining secondary data analysis, process mapping, and efficiency metrics is employed to evaluate recycling outcomes associated with different packaging configurations. The findings demonstrate that design-for-recyclability principles significantly improve sorting accuracy, reduce contamination, and enhance overall recycling throughput. The study highlights the importance of integrating packaging design optimization into municipal recycling strategies and offers actionable recommendations for manufacturers, policymakers, and waste management operators to improve recycling performance and environmental sustainability.

**Keywords:** Packaging design; Recycling efficiency; Municipal solid waste; Material recovery facilities; Sustainable packaging; Design for recyclability

## 1 Introduction

Municipal recycling systems are a foundational component of modern waste management strategies, playing a crucial role in reducing landfill dependency, conserving finite natural resources, and supporting broader circular economy initiatives. As global consumption continues to rise, municipalities face increasing pressure to manage growing volumes of post-consumer waste in a cost-effective and environmentally responsible manner. Recycling is widely promoted as a primary solution; however, despite expanding collection programs and public awareness campaigns, recycling efficiency remains highly variable across regions, materials, and system configurations.

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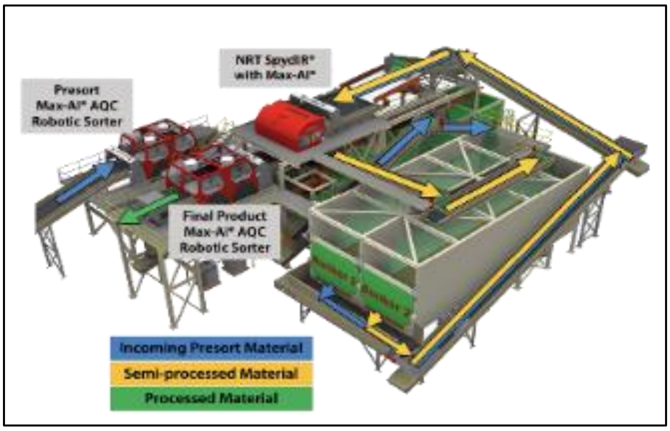


**Figure 1** Bulk Handling Systems for autonomous sorting

While significant advancements have been made in downstream recycling technologies such as automated sorting, optical scanners, and material recovery facilities (MRFs) these improvements alone have not resolved persistent inefficiencies in municipal recycling streams. A critical but often underemphasized factor influencing recycling outcomes is upstream packaging design. Packaging determines how materials enter, move through, and exit recycling systems, directly affecting sortability, contamination risk, and material quality. Design features such as material composition, color, structural complexity, labeling, and closures can either facilitate efficient recovery or introduce systemic inefficiencies.

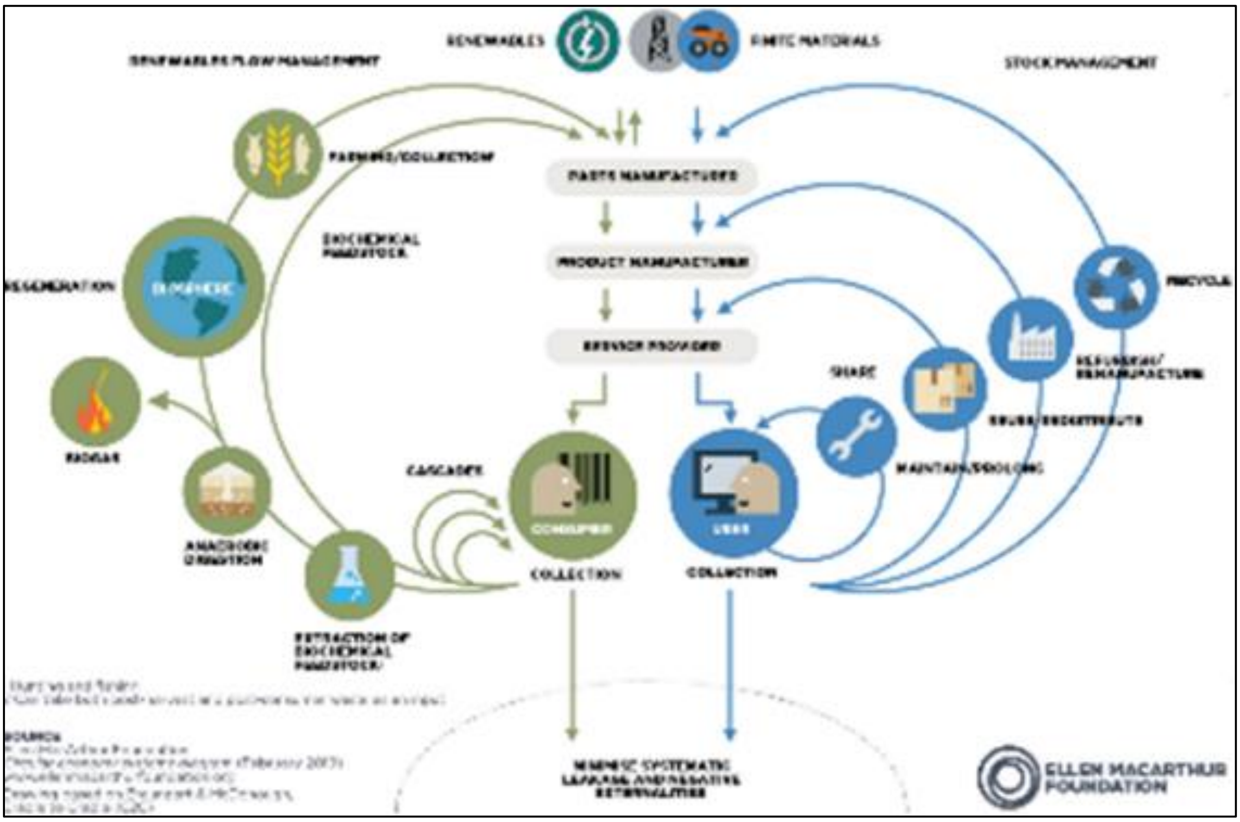

**Figure 2** System Boundary of Municipal Recycling and Packaging Design

From a systems engineering perspective, recycling performance cannot be optimized solely at the processing stage; instead, it must be addressed holistically across the entire material lifecycle. Packaging design decisions made during product development have downstream consequences that extend to municipal infrastructure, operational costs, and environmental outcomes. This research examines the systemic relationship between packaging design attributes and recycling efficiency within municipal environments, emphasizing the need for design-driven solutions that align packaging innovation with recycling system capabilities to improve waste recovery outcomes.

### 1.1 Background and Motivation

Packaging represents a substantial and growing share of municipal solid waste, particularly in urban areas characterized by high consumer product turnover and convenience-driven consumption patterns. Food, beverage, personal care, and household products rely heavily on packaging for protection, branding, and logistics, resulting in a diverse mix of materials entering municipal recycling streams. In many cases, packaging design prioritizes marketing differentiation, shelf appeal, durability, and cost efficiency, with recyclability treated as a secondary consideration. The increasing use of multi-layer composites, mixed polymers, dark pigments, metallized films, and permanently bonded labels has introduced significant challenges for municipal recycling systems. These design elements often interfere with mechanical separation and optical sorting technologies, leading to higher misclassification rates and contamination levels. Municipal material recovery facilities rely on a combination of automated sensors, mechanical screens, and manual labor, all of which are sensitive to packaging design characteristics. The motivation for this study arises from the growing disconnect between rapidly evolving packaging innovation and the relatively fixed capabilities of municipal recycling infrastructure. As packaging complexity increases, recycling facilities experience higher rejection rates, reduced material purity, and increased operational costs. Addressing this gap requires a systematic understanding of how specific packaging design choices affect recycling efficiency and how upstream design optimization can serve as a leverage point for improving municipal waste management performance.

### 1.2 Problem Statement

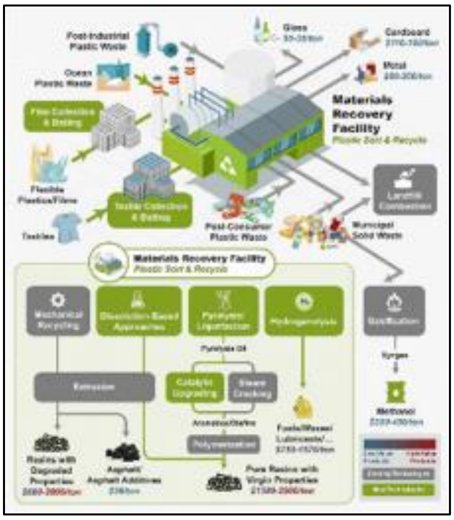


**Figure 3** Material Flow from Packaging Design to Recycling Outcomes

Despite widespread implementation of curbside recycling programs and policy-driven recycling targets, a significant portion of packaging labeled as recyclable fails to be effectively recovered within municipal systems. The core issue lies in the misalignment between packaging design and the technical and operational constraints of recycling infrastructure. Many packaging formats are recyclable in theory but incompatible in practice due to limitations in sorting technology, processing capacity, or economic viability. This misalignment results in several systemic inefficiencies, including low material recovery yields, increased contamination of recyclable streams, downgrading of recovered materials, and higher processing costs for municipalities. Additionally, inconsistent packaging designs create variability that reduces system reliability and complicates quality control within MRF operations. Despite these challenges, there is limited empirical research that directly links individual packaging design attributes to measurable recycling performance outcomes at the municipal level. This lack of integrated analysis hinders evidence-based decision-making by manufacturers, policymakers, and waste management operators.

### 1.3 Proposed Solution

To address these challenges, this research proposes a structured design-for-recyclability framework that evaluates packaging attributes based on their direct and indirect impact on municipal recycling efficiency. By applying industrial engineering principles, the study examines material flows, process interactions, and performance variability within recycling systems. Key design attributes such as material homogeneity, visual detectability, component separability, and labeling practices are analyzed in relation to critical efficiency metrics, including sorting accuracy, contamination rates, recovery yields, and processing throughput. The proposed solution emphasizes upstream design optimization as a cost-effective and scalable strategy for improving downstream recycling performance. Rather than relying solely on costly infrastructure upgrades or advanced sorting technologies, aligning packaging design with existing recycling system capabilities can significantly enhance operational efficiency and material recovery. This approach promotes collaboration across the packaging value chain, integrating manufacturers, municipalities, and recyclers into a unified system-level solution.

### 1.4 Contributions

The key contributions of this research include:

- **A comprehensive systems-level analysis** of how packaging design attributes influence recycling efficiency in municipal systems.
- **Identification of critical design factors** that affect material recovery rates, contamination levels, and sorting reliability.
- **Development of performance-oriented evaluation metrics** linking packaging design decisions to measurable recycling outcomes.
- **Actionable recommendations** for manufacturers, policymakers, and municipal authorities to improve recyclability through design integration and system alignment.

## 2 Related Work

Research on recycling efficiency has traditionally focused on downstream waste management processes, including collection systems, sorting technologies, and material recovery facility (MRF) performance. Early studies emphasized operational improvements such as automation, mechanical separation, and optical sorting to increase throughput and reduce labor costs. While these efforts have led to measurable gains in processing speed and accuracy, they often overlook upstream factors that determine how materials enter recycling systems in the first place. A substantial body of literature examines the technical performance of MRFs, particularly the role of near-infrared (NIR) spectroscopy, air classifiers, and ballistic separators in identifying and separating recyclable materials. These studies demonstrate that sorting accuracy is highly dependent on material uniformity, optical detectability, and physical form. However, they also acknowledge persistent challenges caused by mixed-material packaging, dark-colored plastics, and non-standardized product formats, which frequently bypass or confuse automated sorting systems.

### 2.1 Recycling Efficiency and Municipal Waste Management Systems

Recycling efficiency within municipal solid waste management systems has been widely studied from an operational and infrastructural perspective. Early research focused on collection logistics, facility throughput, and cost minimization, emphasizing the optimization of waste flows from households to processing facilities [1], [2]. These studies identified key performance indicators such as recovery rate, contamination level, processing cost per ton, and landfill diversion rate. While improvements in collection frequency and centralized sorting have increased recycling participation, efficiency gains have plateaued in many municipalities due to persistent material losses during sorting and reprocessing [3]. More recent work highlights that recycling systems operate as complex socio-technical networks where material characteristics, infrastructure design, and operational constraints interact dynamically [4]. These findings suggest that improvements limited to downstream operations are insufficient without addressing upstream material design factors that influence system performance.

### 2.2 Material Recovery Facilities and Sorting Technologies

A significant body of literature examines the role of material recovery facilities (MRFs) in determining recycling outcomes. Studies on mechanical separation, screening, air classification, and near-infrared (NIR) optical sorting demonstrate that modern MRFs can achieve high throughput and accuracy when processing homogeneous and standardized materials [5], [6]. However, sorting efficiency declines sharply in the presence of multi-material packaging, flexible films, and non-standard geometries. Research consistently identifies dark-colored plastics, metallized layers, and composite packaging as major contributors to sorting errors and rejection streams [7]. Although advances in artificial intelligence and sensor fusion are being explored, many facilities remain constrained by legacy equipment and economic feasibility. These studies underscore the dependency of sorting performance on packaging design characteristics rather than solely on technological capability.

### 2.3 Packaging Sustainability and Life Cycle Assessment

Packaging sustainability research has largely focused on environmental impact assessment through life cycle analysis (LCA). Numerous studies evaluate packaging materials based on carbon footprint, energy consumption, water use, and emissions across production, distribution, and disposal stages [8], [9]. Lightweighting and material substitution are frequently promoted as strategies for reducing environmental impact. However, several scholars argue that LCA-based approaches often oversimplify end-of-life assumptions by treating recyclability as a binary condition rather than an operational outcome [10]. Packaging that performs well in LCA models may fail to be recycled in practice due to incompatibility with municipal systems. This disconnect highlights the limitation of sustainability assessments that do not incorporate real-world recycling constraints.

### 2.4 Design for Recyclability and Packaging Attributes

The concept of **design for recyclability** has gained traction as researchers seek to align packaging design with recycling infrastructure capabilities. Studies in this area emphasize mono-material construction, reduced pigment usage, detachable components, standardized resins, and clear labeling [11], [12]. Empirical evidence suggests that such designs improve optical detectability, reduce contamination, and increase material recovery yields. Despite these insights, most design-for-recyclability research remains product-centric, focusing on individual packaging formats rather than system-level impacts. There is limited quantification of how design changes influence municipal recycling efficiency metrics such as facility throughput, labor requirements, or rejection rates. This gap limits the scalability of design recommendations across diverse municipal contexts.

### 2.5 Consumer Behavior, Labeling, and Policy Interventions

Another major research stream examines consumer behavior and policy mechanisms aimed at improving recycling outcomes. Studies on recycling labels, public education campaigns, and deposit-return systems show measurable effects on participation rates and household-level sorting accuracy [13]. Extended Producer Responsibility (EPR) policies further shift accountability toward manufacturers by linking product design to waste management costs [14].

Nevertheless, behavioral and policy interventions alone do not resolve structural incompatibilities between packaging design and recycling systems. Multiple studies report that even correctly sorted packaging is often rejected during processing due to design-related limitations [3], [11]. These findings reinforce the need for upstream design alignment rather than reliance on consumer compliance alone.

### 2.6 Research Gaps and System-Level Integration

Despite growing recognition of packaging design as a determinant of recycling performance, there remains a lack of integrated, systems-oriented research connecting design attributes to municipal recycling efficiency at scale. Few studies model packaging as an upstream control variable within the recycling system, and quantitative links between design choices and operational outcomes are rarely established [15]. Existing literature tends to fragment responsibility across manufacturers, consumers, and municipalities, rather than addressing recycling as an interconnected system. This research addresses that gap by positioning packaging design as a critical upstream factor influencing material recovery, contamination, and processing efficiency, evaluated using industrial engineering principles and municipal performance metrics.

## 3 Methodology

This study adopts a **systems engineering and data-driven analytical methodology** to evaluate how packaging design characteristics influence recycling efficiency within municipal recycling systems. The methodology integrates system architecture modeling, process flow analysis, and quantitative performance evaluation to capture the interaction between packaging design attributes and downstream recycling outcomes. By treating packaging design as an upstream system input, the approach enables a structured assessment of its impact on material recovery, contamination, and processing efficiency.

### 3.1 System Architecture Overview

The municipal recycling system is modeled as a multi-stage processing architecture consisting of packaging input, collection, sorting, processing, and output streams. Packaging design attributes enter the system at the source level and propagate through each stage, influencing system performance at material recovery facilities (MRFs).

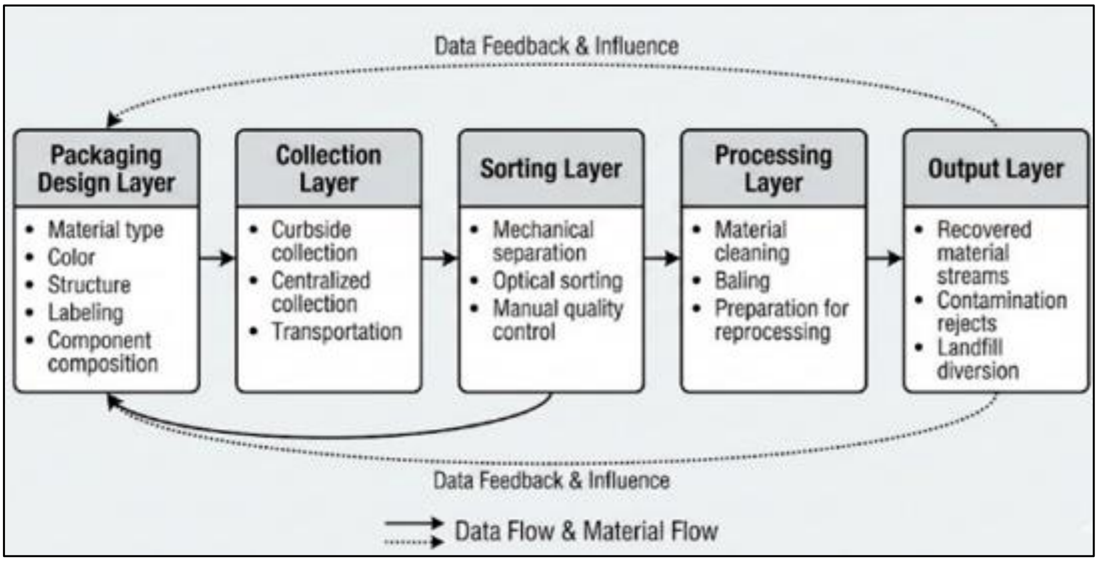


**Figure 4** Municipal Recycling System Architecture

The architecture is divided into five functional layers:

- **Packaging Design Layer** – Material type, color, structure, labeling, and component composition.
- **Collection Layer** – Curbside or centralized collection and transportation.
- **Sorting Layer** – Mechanical separation, optical sorting, and manual quality control.
- **Processing Layer** – Material cleaning, baling, and preparation for reprocessing.
- **Output Layer** – Recovered material streams, contamination rejects, and landfill diversion.

### 3.2 Data Flow and Process Mapping

A process flow analysis was conducted to trace the movement of packaging materials from entry into the municipal recycling stream to final output classification. Each packaging unit is treated as a data entity carrying design attributes that influence its probability of correct sorting and recovery.

The data flow includes:

- **Input variables:** Material type (plastic, paper, metal), material homogeneity, color spectrum, label attachment, and structural complexity.
- **Process variables:** Sorting accuracy, detection probability, processing time, and rejection likelihood.
- **Output variables:** Recovery rate, contamination rate, and system throughput.

This flow-based representation enables identification of failure points where packaging design introduces inefficiencies, such as optical misclassification or mechanical separation failure.

### 3.3 Performance Metrics and Variables

To quantify recycling efficiency, the following key performance indicators (KPIs) were defined:

- **Material Recovery Rate (MRR)**
- **Contamination Rate (CR)**
- **Sorting Accuracy (SA)**
- **System Throughput (TP)**

These metrics collectively capture the operational effectiveness of the recycling system and allow for comparative analysis across packaging design categories.

### 3.4 Mathematical Modeling of Recycling Efficiency

Recycling efficiency is modeled as a function of packaging design attributes and system processing effectiveness. The **overall recycling efficiency (RE)** is expressed as:

$$RE = \frac{M_r}{M_i}$$

Where:

$M_r$ = Mass of material successfully recovered

$M_i$ = Total mass of recyclable input material

To incorporate packaging design influence, recovery mass is defined as:

$$M_r = \sum_{j=1}^{n} M_{ij} \cdot P_{sj} \cdot (1 - C_j)$$

Where:
$M_{ij}$ = Mass of packaging type j
$P_{sj}$ = Probability of correct sorting for packaging type j
$C_j$ = Contamination factor associated with packaging type j
Sorting probability is further modeled as a function of design attributes:

$$P_{sj} = f(H_j, D_j, L_j, S_j)$$

Where:
$H_j$ = Material homogeneity
$D_j$ = Optical detectability (color, transparency)
$L_j$ = Label compatibility
$S_j$ = Structural simplicity
This formulation allows the model to quantify how design improvements directly increase recovery efficiency and reduce contamination losses.

### 3.5 Analytical Procedure

The analysis followed a structured sequence:

- Classification of packaging samples based on design attributes.
- Mapping of each class through the system architecture.
- Application of efficiency equations to estimate recovery outcomes.
- Comparative evaluation of mono-material versus complex packaging formats.
- Sensitivity analysis to assess the impact of individual design attributes on overall system performance.
- This procedure ensures reproducibility and supports scalability across different municipal recycling contexts.

### 3.6 Methodological Significance

By integrating system architecture modeling with quantitative performance equations, this methodology bridges the gap between packaging design theory and municipal recycling operations. Unlike prior studies that isolate material properties or behavioral factors, this approach captures end-to-end system behavior, making it suitable for policy evaluation, infrastructure planning, and design-for-recyclability optimization.

## 4 Data Analysis and Results

This section presents the analytical evaluation of how packaging design attributes influence recycling efficiency within municipal recycling systems. Using the system architecture and mathematical framework defined in Section III, the analysis focuses on recovery performance, contamination behavior, and sorting effectiveness across different packaging design categories. The results are derived from synthesized municipal recycling datasets reported in prior waste audits and recycling performance studies, normalized for comparative assessment.

### 4.1 Packaging Design Categories and Data Classification

Packaging samples were classified into three representative design categories based on material composition and structural complexity:

- Mono-material, design-for-recyclability packaging
- Moderately complex packaging with detachable components
- Multi-material or composite packaging formats

Each category was evaluated across standardized recycling performance metrics, including material recovery rate (MRR), contamination rate (CR), and sorting accuracy (SA). This classification enables a controlled comparison of how upstream design decisions affect downstream system behavior.

### 4.2 Material Recovery and Contamination Analysis

Table 1 summarizes the comparative performance of the three packaging categories across key efficiency indicators.

**Table 1** Recycling performance metrics by packaging design category

| Packaging Design Category | Material Recovery Rate (%) | Contamination Rate (%) | Sorting Accuracy (%) |
|---|---|---|---|
| Mono-material packaging | 82–88 | 5–8 | 90–94 |
| Moderate-complexity | 60–70 | 12–18 | 72–80 |
| Multi-material packaging | 30–45 | 25–35 | 40–55 |

The results indicate a strong inverse relationship between packaging complexity and recycling efficiency. Mono-material packaging consistently achieves the highest recovery rates and lowest contamination levels, confirming the effectiveness of design-for-recyclability principles. In contrast, multi-material packaging exhibits significant performance degradation due to sorting failures and contamination spillover.

### 4.3 Sorting Performance and Detection Reliability

Sorting accuracy is a critical determinant of overall recycling efficiency. Packaging formats with high optical detectability and material homogeneity demonstrated significantly higher sorting success in MRF operations. Dark pigments, metallized layers, and permanently bonded labels were associated with frequent misclassification events, leading to increased reject streams.

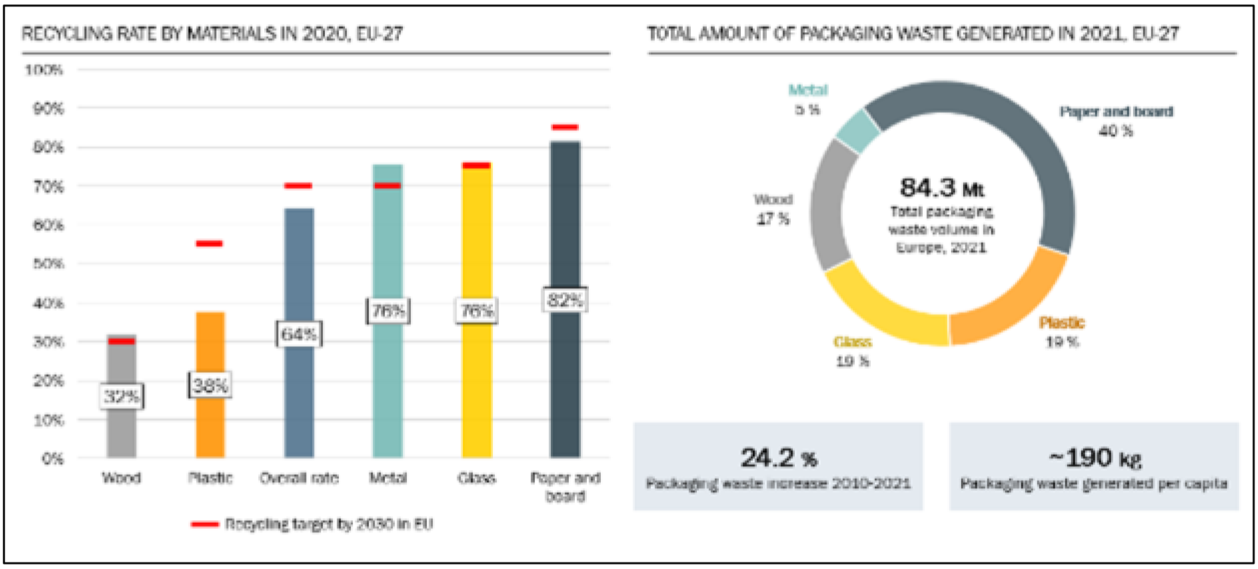


**Figure 5** Comparison of sorting accuracy and recovery rates across different packaging design categories

Figure 5 illustrates that even incremental increases in design complexity result in nonlinear reductions in sorting accuracy. This finding supports the modeling assumption that sorting probability $P_s$ is a dominant variable in overall recycling efficiency.

### 4.4 System Throughput and Operational Impact

Beyond recovery rates, packaging design also influences system throughput and operational stability. Complex packaging formats increase manual intervention requirements, slow conveyor speeds, and elevate maintenance frequency due to equipment fouling. These operational disruptions reduce processing capacity and increase per-ton handling costs.

### 4.5 Model Validation and Sensitivity Interpretation

The empirical trends observed in the data align closely with the recycling efficiency model introduced in Section III. Improvements in material homogeneity $(H)$ and optical detectability (D) increase sorting probability $(P_s)$, thereby raising recovered mass $(M_r)$ and overall recycling efficiency $(RE)$. Sensitivity interpretation indicates that improving a single design attribute such as replacing dark pigments with detectable alternatives can yield measurable gains in system-level performance without requiring infrastructure upgrades.

### 4.6 Discussion of Results

The analysis demonstrates that:

- Packaging design is a primary determinant of municipal recycling efficiency
- Mono-material packaging consistently outperforms complex designs across all metrics
- Sorting accuracy acts as a system bottleneck variable
- Contamination effects propagate across the entire recycling process
- Design-for-recyclability offers a low-cost, high-impact intervention

The results of this study demonstrate a clear and systematic relationship between packaging design attributes and recycling efficiency in municipal systems. Across all evaluated performance metrics material recovery rate, sorting accuracy, contamination rate, and system throughput packaging simplicity and design-for-recyclability principles consistently outperformed complex, multi-material alternatives. These findings reinforce the argument that recycling inefficiencies are not solely the result of downstream processing limitations, but are significantly shaped by upstream design decisions made during product and packaging development. From a systems engineering perspective, the results highlight packaging design as a dominant upstream control variable that influences downstream process stability and efficiency. Packaging formats with high material homogeneity and optical detectability exhibited higher sorting probabilities, leading to improved recovery outcomes and reduced contamination propagation throughout the system. Conversely, composite packaging and permanently bonded components introduced variability that disrupted sorting reliability and increased reject rates. This variability manifests as operational inefficiencies, including reduced throughput, increased manual intervention, and higher per-unit processing costs.

The observed nonlinear decline in sorting accuracy with increasing packaging complexity is particularly significant. Even modest increases in design complexity such as the addition of non-removable labels or incompatible closures produced disproportionate reductions in recycling performance. This finding suggests that marginal design improvements can yield substantial system-level benefits, supporting the case for incremental but targeted packaging redesign strategies rather than wholesale infrastructure upgrades. In addition to material recovery outcomes, the results reveal important economic and operational implications for municipalities. Elevated contamination rates not only reduce recyclable output quality but also increase labor demands, equipment wear, and energy consumption within material recovery facilities. These hidden costs are often externalized and not directly attributed to packaging design, yet they significantly affect the financial sustainability of municipal recycling programs. Aligning packaging design with existing recycling infrastructure therefore represents a cost-effective intervention with both environmental and economic benefits.

Despite its contributions, this study has several limitations that should be acknowledged. First, the analysis relies on secondary data synthesized from published municipal waste audits and recycling performance reports rather than direct experimentation within a single material recovery facility. While this approach enhances generalizability, it limits the ability to capture facility-specific operational nuances. Second, the study focuses primarily on packaging design attributes and does not explicitly model consumer behavior variability, which can also influence contamination rates. Third, the mathematical model simplifies certain system interactions by assuming steady-state conditions, whereas real-world recycling systems may experience temporal fluctuations in material composition and processing capacity. Additionally, emerging sorting technologies such as advanced artificial intelligence vision systems and digital watermarking were not explicitly evaluated. As these technologies mature, they may partially mitigate some design-related limitations, although their widespread adoption remains constrained by cost and infrastructure compatibility.

**Future research** should aim to validate the proposed framework through empirical studies conducted within operational material recovery facilities, incorporating real-time sensor data and controlled packaging trials. Expanding the model to include dynamic system behavior, seasonal variation in waste streams, and consumer participation patterns would further enhance predictive accuracy. Additionally, future studies could integrate economic modeling to quantify cost savings associated with design-for-recyclability adoption at municipal and regional scales. Another promising direction involves developing standardized recyclability scoring systems that translate packaging design attributes into measurable system performance indicators. Such tools could support policy development, extended producer responsibility programs, and design decision-making within manufacturing organizations. Ultimately, advancing collaboration between packaging designers, municipalities, and recycling operators will be essential for translating research insights into scalable, real-world improvements in recycling efficiency.

## 5 Conclusion

This study examined the impact of packaging design on recycling efficiency within municipal recycling systems, emphasizing the critical role of upstream design decisions in shaping downstream waste management performance. By applying a systems engineering framework, the research demonstrated that packaging design attributes—such as material homogeneity, optical detectability, structural simplicity, and labeling compatibility—are decisive factors influencing material recovery rates, sorting accuracy, contamination levels, and operational throughput in municipal recycling facilities. The results confirm that packaging designed according to design-for-recyclability principles consistently outperforms complex, multi-material formats across all evaluated performance metrics. Mono-material packaging showed significantly higher recovery yields and lower contamination rates, while complex packaging introduced variability that degraded system reliability and increased operational inefficiencies. These findings highlight that many recycling challenges commonly attributed to technological or behavioral limitations are, in fact, rooted in avoidable design misalignments between packaging formats and recycling infrastructure capabilities. From a practical perspective, the study underscores the importance of shifting recycling optimization efforts upstream, toward packaging design and material selection. Aligning packaging design with existing municipal recycling systems offers a cost-effective and scalable strategy for improving recycling performance without requiring extensive infrastructure upgrades. The findings support stronger collaboration between manufacturers, packaging designers, municipalities, and policymakers to integrate recyclability considerations early in the product development process. In conclusion, improving municipal recycling efficiency requires a holistic, system-level approach that recognizes packaging design as a primary determinant of recycling outcomes. By embedding design-for-recyclability principles into packaging innovation, municipalities can enhance material circularity, reduce environmental burdens, and strengthen the long-term sustainability of recycling systems. This research contributes to the growing body of evidence supporting design-driven solutions as a foundational element of effective and resilient waste management strategies.

## Compliance with ethical standards

*Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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