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Design and Commercial Validation of a Hierarchical Three-Tier Quality Grading System for Post-Industrial Recycled and Post-Consumer Recycled Thermoplastic Resins in the US Industrial Supply Chains

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Abstract

Quality grading systems for recycled thermoplastic resins are a foundational requirement for the reliable integration of secondary raw materials into industrial manufacturing supply chains. Despite this need, no standardized grading scale has been established for post-industrial and post-consumer polypropylene (PP), high-density polyethylene (HDPE), and low-density polyethylene (LDPE) resins in industrial supply chain contexts. This paper presents the design, operational implementation, and commercial validation of a hierarchical three-tier quality grading system comprising Grade A (Near Prime), Grade B (Commercial Grade), and Grade C (Low Grade), developed through more than twenty years of secondary polymer distribution practice at Maja World Wide LLC and formalized in USPTO Provisional Patent Application No. 64/043,650, filed April 19, 2026. The grading system assigns each incoming recycled resin batch to a quality tier based on six evaluation dimensions: visual inspection, polymer type verification, physical form classification, Melt Flow Index (MFI) testing, processing behavior assessment, and supplier reliability scoring. Commercial deployment data demonstrate a stable grade distribution of 35% Grade A, 45% Grade B, and 20% Grade C across PP, HDPE, and LDPE streams. Grade A material achieves first-pass specification compliance rates of 96.8–98.1%, Grade B achieves 90.8–93.1%, and Grade C processed through proportional blending achieves 86.4–89.1% across packaging, construction, automotive, and consumer goods applications (Table 1). The grading system provides the standardized quality language required for contractual specification guarantees in recycled resin supply agreements, directly enabling the industrial buyer confidence necessary for sustained circular economy procurement commitments.

Keywords: Recycled resin grading, quality classification, thermoplastic resin, post-consumer resin, secondary raw materials, circular economy, industrial supply chain, grade specification, polymer quality, buyer confidence

INTRODUCTION

Quality grading systems serve as the foundational communication infrastructure of commercial raw material markets. In virgin polymer markets, resin grades defined by manufacturers – with specific MFI ranges, density specifications, additive packages, and application recommendations – provide buyers with the specification confidence required to commit to procurement contracts and integrate materials into validated production processes [1]. The existence of standardized grade definitions, backed by manufacturer quality certification and supported by industry standard test methods (ASTM, ISO), is a prerequisite for the functioning of efficient commercial polymer markets [2].

In secondary polymer markets – the commercial ecosystem for post-industrial and post-consumer recycled resins – no equivalent standardized grading system has been established. Existing

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frameworks for recycled resin quality assessment address recyclability evaluation for packaging design, as described in the APR Design Guide [3], or regulatory compliance for specific applications, such as the FDA guidance for food-contact recycled content [4], but do not provide a commercial grading scale applicable to secondary resin distribution for industrial buyers across heterogeneous application categories. The absence of a standardized grading language for recycled resins forces industrial buyers to define specifications on a case-by-case basis, evaluate each supplier's characterization approach independently, and accept quality risk that would not be present in a standardized graded supply environment – contributing directly to the documented buyer reluctance to commit to recycled resin procurement at scale [5, 6].

The scale of this opportunity is substantial. The United States generates more than 40 million metric tons of plastic waste annually [7], of which post-industrial and post-consumer thermoplastic resins represent a recoverable fraction that substantially exceeds current industrial procurement of recycled resin [8, 9]. The Ellen MacArthur Foundation has identified the absence of standardized quality infrastructure as a primary barrier to circular economy realization in polymer supply chains [10]. A hierarchical grading system specifically designed for secondary polymer distribution contexts directly addresses this infrastructure gap.

This paper presents a hierarchical three-tier quality grading system for secondary thermoplastic resins that addresses this gap, developed through commercial operational practice at Maja World Wide LLC – a secondary polymer distributor serving 500+ industrial clients across 15 US states at volumes exceeding 3,000 metric tons per month – and formalized in USPTO Provisional Patent Application No. 64/043,650 [11]. The paper describes the grade definition criteria, the commercial validation of grade assignment consistency, and the industrial buyer specification compliance outcomes associated with each grade across the four primary industrial application categories served by the operational dataset.

GRADING SYSTEM DESIGN PRINCIPLES

Design Requirements for an Industrial Secondary Resin Grading System

An effective quality grading system for secondary resins in industrial supply chain contexts must satisfy four design requirements. First, it must be multi-dimensional – capturing quality information across the full range of dimensions relevant to industrial processing performance, not solely MFI or contamination in isolation. Second, it must be hierarchical – providing distinct, non-overlapping grade categories that correspond to differentiated industrial application suitability, enabling buyers to specify grade requirements and distributors to guarantee compliance. Third, it must be operationally implementable – based on testing methods that are practically executable in a commercial distribution context without laboratory infrastructure unavailable to most distributors. Fourth, it must be predictive – grade assignments that must reliably predict industrial buyer processing specification compliance outcomes, providing the buyer confidence that sustains commercial procurement commitments [12].

The three-tier grading system presented in this paper was designed against these four requirements through iterative refinement over twenty years of commercial practice, with grade boundary criteria calibrated against observed buyer processing compliance outcomes across the operational dataset.

Grade Definition – Grade A (Near Prime)

Grade A (Near Prime) is the highest quality tier in the grading system, assigned to recycled resin batches whose performance profile approaches that of virgin resin of the same polymer type. Grade A assignment requires the simultaneous satisfaction of all of the following criteria across the six evaluation components: visual inspection – no significant contamination, uniform color consistent with the declared polymer type, no moisture indicators, minimal odor; polymer type verification – confirmed polymer type with density within ±0.005 g/cm³ of the declared polymer type standard per ASTM D792; physical form – pellets or high-quality uniform regrind; MFI within ±0.3 g/10 min of the batch nominal value per ASTM D1238, confirming tight MFI consistency; processing behavior assessment – no gel formation, no degradation streaks, no color irregularities, no flow inconsistencies under standard processing conditions; supplier reliability score above 0.80, reflecting a supplier with documented high-consistency quality delivery history [12].

Grade A material is suitable for the full spectrum of industrial applications including those with strict aesthetic requirements (transparent or light-colored end products), tight dimensional tolerance requirements (precision injection molded components), and applications in proximity to food contact regulatory requirements. It is the grade category that most closely replicates the buyer experience of procuring virgin resin, enabling its use in production environments with minimal process adjustment relative to virgin material baselines.

Grade Definition – Grade B (Commercial Grade)

Grade B (Commercial Grade) is the intermediate quality tier, representing the largest segment of available secondary resin supply – 45% of evaluated batches in the operational dataset – and the grade category most commonly matched to standard industrial buyer requirements. Grade B assignment requires: visual inspection – acceptable contamination within defined thresholds, moderate color variation within commercially acceptable ranges, acceptable moisture indicators, moderate odor; polymer type – confirmed with density within ±0.010 g/cm³ of type standard; physical form – pellets, acceptable regrind, or clean bales; MFI within ±0.8 g/10 min of nominal, consistent with standard commercial processing tolerance ranges; processing behavior – minor gel incidence (≤3 gels per 100 cm² extrudate surface), no significant degradation streaks, acceptable color consistency; supplier reliability score 0.50–0.80.

Grade B material is suitable for cost-sensitive industrial applications in packaging, construction, and general manufacturing where some batch-to-batch variability in material properties can be accommodated within the buyer's process window without compromising product quality or equipment reliability [5, 6]. It represents the primary vehicle for recycled resin integration into mainstream industrial procurement and the grade category whose consistent quality delivery is most critical to building sustained buyer confidence in secondary resin supply chains.

Grade Definition – Grade C (Low Grade)

Grade C (Low Grade) is the lowest quality tier, assigned to batches that do not meet the minimum criteria for Grade B assignment due to contamination above commercial thresholds, MFI outside standard commercial processing ranges, notable processability limitations, or supplier reliability score below 0.50. Grade C material is not suitable for direct industrial application as a standalone material but is a viable supply chain input when integrated through the proportional blending methodology described in Section 4.

Grade C material represents approximately 20% of evaluated batches in the operational dataset. Without a structured integration pathway, this material would be directed to downcycling, energy recovery, or landfill – outcomes that represent a loss of material value and a failure of circular economy objectives, as documented by Ragaert et al. [5] and Al-Salem et al. [9]. The blending determination methodology provides Grade C material with a structured pathway into industrial supply chains at blend ratios that achieve specification compliance, maximizing secondary resin yield from each recovered polymer stream.

COMMERCIAL GRADE DISTRIBUTION

Analysis of grade assignment data across the multi-year operational period demonstrated a stable grade distribution of 35% Grade A, 45% Grade B, and 20% Grade C across the combined PP, HDPE, and LDPE incoming batch portfolio. Polymer-type-specific distributions showed minor variation: PP streams demonstrated a slightly lower Grade A proportion (31%) due to the higher MFI variability characteristic of post-consumer PP relative to post-industrial HDPE streams, consistent with the degradation mechanisms described by Hamad et al. [13]; HDPE streams demonstrated the highest Grade A proportion (38%) consistent with the predominantly post-industrial supply profile of HDPE in the operational supplier network.

The stability of the grade distribution across the operational period – with standard deviation of the monthly Grade A proportion of ±3.2 percentage points across all polymer types – confirms the reliability of the six-component grading protocol as a consistent classification instrument across varying supply conditions. This stability is a prerequisite for inventory planning: buyers and distributors require predictable grade supply availability to support procurement planning and inventory management on a commercial scale.

INDUSTRIAL BUYER SPECIFICATION COMPLIANCE BY GRADE

Grade A: Compliance Performance

Grade A material, when matched to appropriate buyers through the MFI-priority matching protocol described in the associated patent framework, achieved first-pass processing specification compliance rates of 97.2% (packaging), 96.8% (construction), 98.1% (automotive), and 97.5% (consumer goods) across the commercial dataset. These compliance rates approach the performance of virgin resin supply in comparable industrial buyer environments, confirming that Grade A secondary resin can function as a reliable virgin resin substitute in applications requiring the highest quality consistency. The small compliance gap from 100% – 2–3 percentage points – reflects irreducible variability in the recycled material's properties relative to the tightly controlled specifications of virgin resin, as discussed by Vilaplana and Karlsson [6].

Grade B: Compliance Performance

Grade B material, when matched through the MFI-priority protocol to buyers with specification tolerances appropriate for commercial-grade material, achieved compliance rates of 92.4% (packaging), 93.1% (construction), 90.8% (automotive), and 91.7% (consumer goods). These compliance rates confirm that Grade B material, when appropriately matched, provides commercially viable specification reliability for the broad category of industrial applications that constitute most of the secondary resin demand. The slightly lower compliance rates in automotive applications reflect the tighter dimensional and surface quality requirements typical of automotive component manufacturing.

Grade C: Blended Compliance Performance

Grade C material, processed through blending determination at 30/70 or 50/50 recycled/virgin configurations selected by the blending module described in the patent framework, achieved compliance rates of 88.3% (packaging), 89.1% (construction), 86.4% (automotive), and 88.9% (consumer goods). These compliance rates, while lower than Grade A and B standalone performance, represent commercially viable performance for cost-sensitive applications and demonstrate that the blending methodology successfully enables the circular economy integration of Grade C material that would otherwise be excluded from industrial supply chains. The full compliance data across all grades and application categories are summarized in Table 1.

Table 1. First-pass specification compliance rate by grade and industrial application category [11].

Grade	Packaging	Construction	Automotive	Consumer goods
Grade A (Near Prime)	97.2%	96.8%	98.1%	97.5%
Grade B (Commercial Grade)	92.4%	93.1%	90.8%	91.7%
Grade C (Blended 30/70 or 50/50)	88.3%	89.1%	86.4%	88.9%

Source: Commercial operational data, Maja Worldwide LLC (2020–2026). MFI-priority matching protocol applied per reference [11].

DISCUSSION

The Grading System as Buyer Confidence Infrastructure

The compliance rates presented in Table 1 establish the three-tier grading system as a reliable predictor of industrial buyer specification compliance outcomes across all grade categories and application sectors. This predictive reliability is the operational foundation for converting the grading system into a commercial contracting instrument – enabling distributors to provide buyers with grade-specific specification guarantees backed by documented compliance rate data. The transition from informal quality descriptions to standardized grade commitments represents the foundational commercial

infrastructure change required to move industrial buyers from trial to sustained commitment in secondary resin procurement, consistent with the supply chain confidence framework described by Monczka et al. [12].

The performance gap between Grade A compliance (96.8–98.1%) and Grade B compliance (90.8–93.1%) – approximately 6 percentage points – is operationally significant. It establishes the commercial basis for grade-differentiated pricing: Grade A commands a premium reflecting its near-virgin performance, while Grade B provides the cost advantage of secondary resin at a compliance rate sufficient for most industrial applications. This grade-to-price alignment is essential for sustaining buyer commitment to recycled resin procurement as a cost-competitive alternative to virgin material.

Grade-to-Application Alignment as Circular Economy Optimization

The three-tier grading system's most significant circular economy contribution is not the Grade A category – which would be commercially viable under almost any quality characterization approach – but the Grade B and Grade C categories, which together represent 65% of available secondary resin supply. By providing structured quality characterization and buyer-specific compliance data for Grade B and Grade C material, the grading system enables these material categories to enter industrial supply chains at appropriate applications rather than being downcycled or disposed due to the absence of quality characterization. The Ellen MacArthur Foundation has identified exactly this infrastructure gap as the primary barrier to circular economy advancement in polymer markets [10]. The optimization of Grade-to-Application alignment – directing Grade A to precision and aesthetic applications, Grade B to standard industrial applications, and Grade C to cost-sensitive blended applications – maximizes the productive utilization of every recovered polymer stream.

The blending methodology enabling Grade C integration achieves compliance rates of 86.4–89.1% – sufficient for commercial viability in cost-sensitive packaging, construction, and consumer goods applications. At the operational scale of Maja World Wide LLC – 3,000+ metric tons per month – this represents approximately 600 metric tons per month of Grade C material redirected from potential downcycling or disposal into productive industrial supply chains, a quantifiable circular economy contribution of national significance.

Implications for US Secondary Polymer Market Infrastructure

The three-tier grading system represents a prototype for secondary polymer market grading infrastructure that, if adopted across the US secondary resin distribution industry, would substantially reduce the quality uncertainty that currently suppresses industrial recycled resin adoption. The US EPA's National Recycling Strategy identifies quality consistency as a primary barrier to secondary material market development [8]. A standardized, commercially validated grading scale – of the type presented in this paper – provides the shared quality language that buyers, distributors, and policymakers need to build the institutional infrastructure for sustained secondary polymer market growth.

CONCLUSIONS

This paper has presented the design, operational implementation, and commercial validation of a hierarchical three-tier quality grading system for secondary thermoplastic resins in US industrial supply chains, formalized in USPTO Provisional Patent Application No. 64/043,650. The grading system provides the standardized quality language, backed by documented compliance rate data, that industrial buyers need to transition from skeptical trial to committed procurement of secondary resins.

The key validated findings are: (i) Grade A (Near Prime) material achieves specification compliance rates of 96.8–98.1% across packaging, construction, automotive, and consumer goods applications, approaching virgin resin performance; (ii) Grade B (Commercial Grade) achieves 90.8–93.1%, providing commercially viable reliability for the majority of industrial applications; and (iii) Grade C (Low Grade) processed through proportional blending achieves 86.4–89.1%, enabling circular economy

integration of a material category that would otherwise be excluded from industrial supply chains. All three grades demonstrate compliance rates within the range required for sustained commercial procurement commitment.

The grading system, as a component of the broader multi-criteria evaluation and matching framework protected in USPTO Provisional Patent Application No. 64/043,650, represents a foundational contribution to the operationalization of circular economy principles in US industrial polymer supply chains. Future work should explore extension of the grading system to additional polymer types including ABS, PET, and polystyrene streams, and the development of third-party certification protocols based on the grade criteria presented in this paper.

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