Waste Paper as Feedstock for Dissolving Grade Pulp Production. Challenges and Opportunities: A Review

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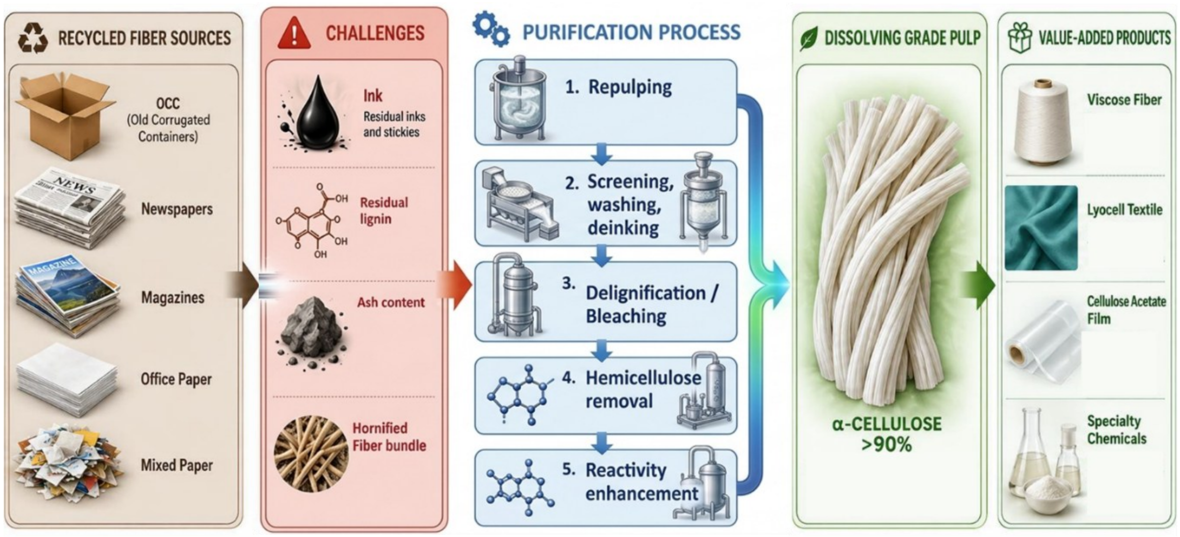
DOI: 10.15376/biores.21.4.Moran

GRAPHICAL ABSTRACT



Waste Paper as Feedstock for Dissolving Grade Pulp Production. Challenges and Opportunities: A Review

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Dissolving-grade pulp (DGP) is a high-purity cellulose feedstock used in the manufacture of regenerated cellulose fibers and cellulose derivatives. Global DGP production is concentrated in regions with established forest-based industries and relies primarily on virgin lignocellulosic resources, including cotton linters, hardwoods, softwoods, and bamboo. These raw materials are typically processed through acid sulfite or prehydrolysis kraft pulping to achieve alpha-cellulose contents above 90%. Compared with virgin feedstocks, recycled fibers exhibit greater variability in morphology and chemical composition, including shorter fiber lengths, lower cellulose quality, and higher levels of residual lignin, ash, inks, fillers, coatings, and other papermaking additives. Consequently, major waste paper streams, such as old corrugated container (OCC), old newspaper (ONP), old magazine (OMG), sorted office paper (SOP), and mixed paper (MP), present distinct challenges for meeting DGP quality specifications. Producing DGP from these secondary fiber resources requires the application of key pulp and paper processing technologies, including repulping, screening, advanced washing and deinking, delignification and bleaching, selective hemicellulose removal through alkaline and enzyme-assisted treatments, and cellulose reactivity enhancement. This review evaluates the technical feasibility of producing DGP from waste paper and highlights both the challenges and opportunities associated with valorizing recycled fibers as a sustainable source of high-purity cellulose.

DOI: 10.15376/biores.21.4.Moran

Keywords: Waste paper; Recovered fibers; Recycling; Dissolving pulp; Cellulose; Enzymes

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INTRODUCTION

Over the years, consumer preferences have increasingly shifted toward sustainable products, positioning recycled paper as a key material for lowering resource consumption, energy use, greenhouse gas emissions, and landfill waste (Aissa and Tampieri 2025). In response, industries have widely adopted eco-design principles, incorporating biomaterials and life cycle analysis to minimize impacts across product lifecycles (Hojnik *et al.* 2019). These practices align with the circular economy, which emphasizes keeping materials in high-value use while regenerating natural systems (Jagoda *et al.* 2023; Simboli *et al.* 2024; Yang *et al.* 2025). The pulp and paper industry fits naturally into this paradigm, with secondary fiber utilization standing as a long-established standard (Ek *et al.* 2009). Globally, paper recovery supports recycling rates near 60%, significantly reducing virgin fiber reliance (Małachowska *et al.* 2023a). In the United States, 2024 paper recycling rates reached 60 to 64% (over 46 million tons) and cardboard reached 69 to 74% (over 33 million tons) (AF&PA 2025). Over two-thirds of this material is processed domestically into containerboard, tissue, newsprint, packaging, or exported globally (AF&PA 2025).

As summarized in Fig. 1, recovered fibers currently serve a well-established cascade of traditional applications, ranging from tissue and hygiene goods to molded pulp, printing papers, and containerboard (McKinney 1995; Gulsoy *et al.* 2013; Sheikhi *et al.* 2013; Chen *et al.* 2015; Didone *et al.* 2017; Ghanbarzadeh *et al.* 2021; Debnath *et al.* 2022; Zhang *et al.* 2022). However, relying exclusively on these conventional outlets exposes the recycling loop to fundamental material limitations. Each progressive recycling cycle degrades fiber length, flexibility, and inter-fiber bonding capacity (Hubbe *et al.* 2007; Furszyfer Del Rio *et al.* 2022). In addition, maintaining paper-grade quality relies heavily on sorting efficiency; poor sorting increases process inefficiencies, compromises product strength, and raises additive consumption (Rao *et al.* 2025; Salem *et al.* 2023).

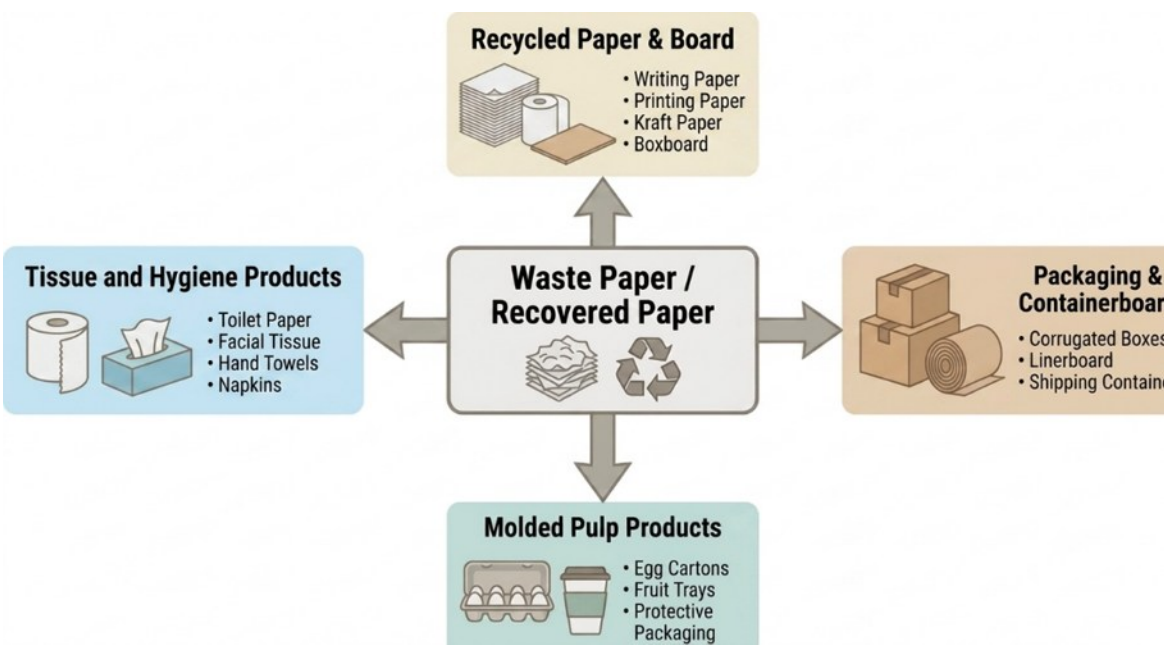

Fig. 1. Applications of wastepaper and recovered fiber

Despite these degradation dynamics, secondary fiber mills contribute 26% of global annual paper production (Małachowska *et al.* 2023b; González *et al.* 2025).

A major intermediate volume driver is deinked pulp (DIP)—derived from old newspapers (ONP), old magazines (OMG), and mixed paper (MP)—which is repulped, washed, and bleached to replace virgin fiber in graphic and tissue papers (Biermann 1996; Jiang and Ma 2000; Hubbe *et al.* 2016a; Sulbarán-Rangel *et al.* 2020). Similarly, low-grade mixed papers find utility in molded pulp items like egg cartons and buffer packaging, where structural formability outweighs optical brightness (Didone *et al.* 2017).

Why Upgrade Waste Paper to Dissolving-Grade Pulp?

While applications such as containerboard and molded pulp successfully absorb high volumes of secondary fibers, they represent low-margin, lower-value cascading outlets that ultimately lead to fiber exhaustion and landfill disposal. Transforming recovered paper into dissolving-grade pulp (DGP) presents a compelling alternative for several key reasons:

1. **Escaping the Fiber Quality Downward Spiral:** In conventional paper packaging, degraded or short fibers directly impair structural strength. In contrast, DGP production chemicalizes the cellulose—extracting and purifying high-alpha cellulose (α-cellulose > 90%) for chemical dissolution and re-spinning into new fibers (*e.g.*, viscose, lyocell) or derivatives (Sixta *et al.* 2013). This breaks the structural degradation cycle of physical paper recycling.
2. **Diversifying beyond Maturing/Declining Packaging Markets:** As global demand for textile fibers accelerates alongside tightening virgin timber availability, upcycling waste paper into DGP opens high-value entry points into multi-billion-dollar bio-textile, pharmaceutical, and specialty chemical markets.
3. **Maximizing Circular Value:** Rather than burning or down-cycling heavily recycled streams, chemical purification provides a true “upcycling” route that preserves pure cellulosic polymer chains within the bioeconomy.

Achieving this transition is technically demanding. Unlike paper pulps, DGP requires strict cellulose purity, minimal lignin/hemicellulose content, and narrow molecular weight distributions (Sixta *et al.* 2013). The inherent heterogeneity of recovered paper—stretching across varied fiber origins, inks, coatings, and fillers—demands intensive chemical purification, deinking, bleaching, and selective hemicellulose extraction (Monte *et al.* 2009; Vilarinho *et al.* 2022; Ghahrani *et al.* 2023).

In this context of expanding scientific interest and evolving technological focus, this review explores practical pathways within secondary fiber mills to transform recovered waste paper fibers into DGP that can meet market specifications. By detailing the structural and chemical changes fibers undergo throughout their lifecycle, we outline processing strategies to optimize resource efficiency, improve product performance, and advance waste paper valorization beyond traditional packaging applications.

Review Methodology

The bibliometric results reveal a marked and sustained growth in scientific interest at the intersection of *Dissolving Pulp, Wastepaper, Paper Recycling, Circular Economy* *and Valorization* over the past two decades (from 2005 to 2025), with a minimum threshold of 5 co-occurrences. The dataset was collected from the *Web of Science (WoS) Core Collection*, comprising more than 780 publications published within the selected time frame. Document types: Review articles, research articles, conference proceedings, and other relevant publications; patents were excluded.

As illustrated in Fig. 2, both the annual number of publications and accumulated citations show a pronounced upward trend, particularly after 2015, indicating the rapid expansion and consolidation of this research field.

The significant increase in output from 2020 onward suggests a growing alignment between high-purity cellulose production and circular economy strategies, where wastepaper is increasingly explored not only as a secondary raw material for conventional paper grades but also as a feedstock for higher-value applications such as dissolving-grade pulp.

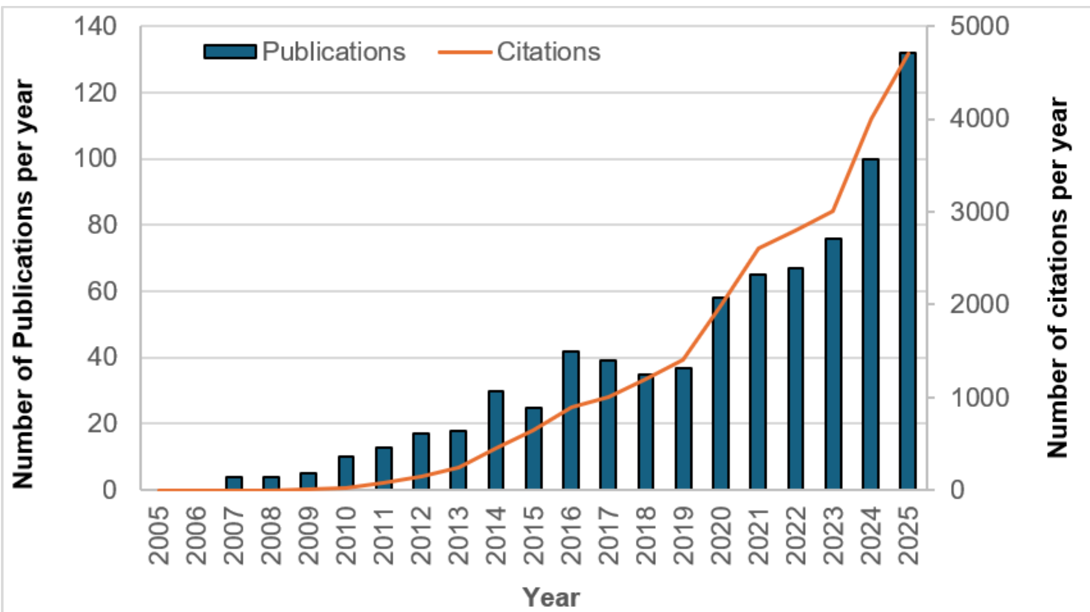

Fig. 2. Times cited and publications over the last 20 years

PRODUCTION OF DISSOLVING GRADE PULPS (DGP)

The production of DGP is more costly than that of paper-grade pulps (PGP) because DGP must satisfy stricter quality requirements (Chen *et al.* 2016; Balkissoon *et al.* 2023; Quintana *et al.* 2024). DGP is primarily used in the production of regenerated cellulose, such as viscose and lyocell, and in selected cellulose-derivative processes, such as cellulose acetate, where high-purity cellulose is required. (Fig. 3). Both of these applications areas require high-purity cellulose with high α-cellulose content, low hemicellulose and inorganic impurities, controlled intrinsic viscosity and degree of polymerization (DP), high reactivity, low alkali solubility, and a narrow molecular weight distribution (Sixta 2006).

For regenerated cellulose, which is used in products such as viscose, lyocell, modal, films, and membranes, DGPs typically require an α-cellulose content above 90 to 94%, hemicellulose below 4%, and low ash and metal contents to ensure efficient dissolution and fiber formation (Li *et al.* 2018; Kosan *et al.* 2024; Frazier *et al.* 2024a). The required pulp properties vary with the processing route, including viscose, lyocell (NMMO), and ionic liquid technologies (Kosan *et al.* 2017).

For cellulose derivatives, including cellulose acetate, cellulose nitrate, methyl cellulose, and carboxymethyl cellulose, pulp quality strongly influences derivatization efficiency and product performance.

In addition to high cellulose purity, these applications require controlled degree of polymerization, low inorganic content, minimal hornification, and high porosity to enable uniform chemical modification (Paunonen *et al.* 2013; Östberg *et al.* 2012; Chen *et al.* 2016; Li *et al.* 2018; Liu *et al.* 2026).

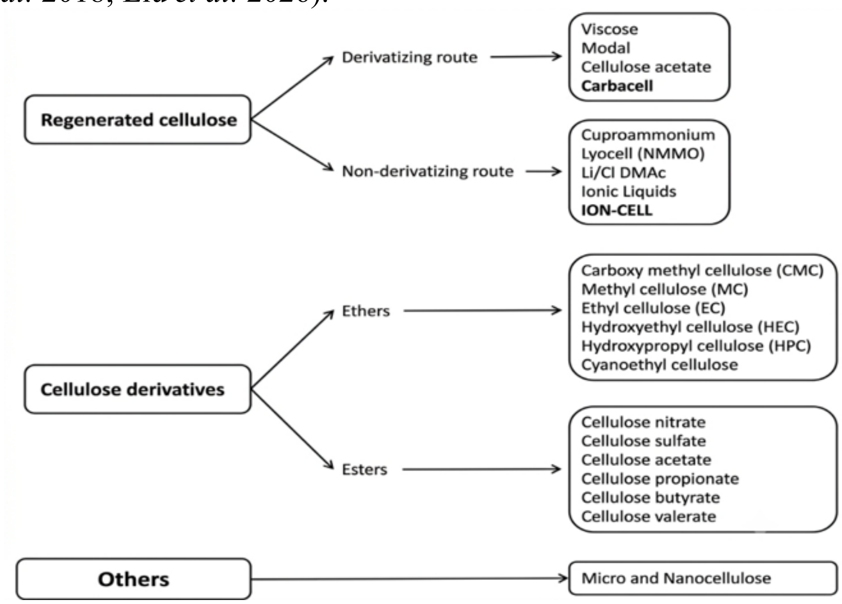

Fig. 3. Dissolving pulp application framework. Adapted from Quintana *et al.* 2024

Current Market of DGP

The global DGP market is experiencing sustained growth, driven by increasing demand across sectors such as textiles, pharmaceuticals, and bioplastics (Chen *et al.* 2016; Quintana *et al.* 2024). As of 2025, the market is valued at over USD 13 billion, with annual production estimated at 11 million tonnes, and continued expansion projected through 2035 (Indexbox 2025).

Production is geographically concentrated in the Asia-Pacific region, particularly China and Indonesia, where low production costs and high domestic demand for textile fibers support large-scale operations (Liu *et al.* 2016; Chen *et al.* 2019a). According to IndexBox data in 2024, Europe produced approximately 2.4 million tonnes of dissolving-grade wood pulp.

The leading producers were Sweden (472,000 tonnes), Austria (426,000 tonnes), and Finland (400,000 tonnes), together accounting for 55% of the total European production. The Czech Republic, Norway, Slovenia, Portugal, Switzerland, and France collectively contributed an additional 40% (IndexBox 2025). North America ranks second largest, with an estimated production of 1.8 million tonnes in 2017. The United States accounted for roughly two-thirds of this total (~1.2 million tonnes), while Canada produced the remaining third (Spectrum Magazine 2017). Brazil is the leading producer in Latin America and ranks third globally, with an annual output nearing 900,000 tonnes (Globalinforesearch 2025).

Though the Middle East and Africa currently have limited production capacity, the region is gaining attention due to its growing emphasis on sustainability and for being home to the world's largest single-site dissolving pulp plant, located in South Africa (Chen *et al.* 2019a; Quintana *et al.* 2024).

The global market is dominated by a few vertically integrated producers with large-scale operations. Among them, Lenzing Group and Sappi Limited are the most prominent, each operating with annual capacities exceeding 1 million tonnes. Lenzing owns and operates pulp mills in Austria, the Czech Republic, and Brazil to support its specialty fiber production. Sappi operates major facilities in South Africa and the United States, including the Saiccor Mill, the world's largest dissolving pulp mill (Jagoda *et al.* 2023). Other major industry players include Aditya Birla Group, Bracell, Rayonier Advanced Materials, and Asia Pulp & Paper (APP), although detailed production capacity data for these firms is less readily available (PR Newswire 2016).

The viscose process, in which cellulose is first converted to alkali cellulose and subsequently reacts with carbon disulfide (CS_2) to form cellulose xanthate, remains the dominant method for producing regenerated cellulosic fibers (Strunk 2012; Chen *et al.* 2016; Liu *et al.* 2016; Frazier *et al.* 2024b; Quintana *et al.* 2024). As illustrated in Fig. 4, in 2020 this method accounted for over 75% of global cellulose fiber production, followed by acetate and other derivatives (Frazier *et al.* 2024b).

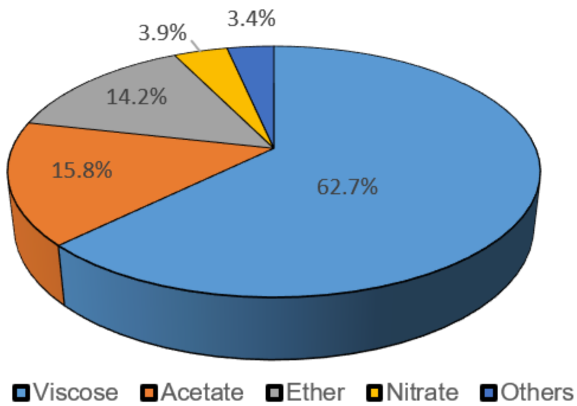

Fig. 4. Market distribution of DGP applications globally. Adapted from Liu *et al.* 2016

DGP Production Processes

The production DGP relies on chemical pulping that makes it possible to obtain high-purity cellulose and low hemicellulose content (Panth 2004; Duan *et al.* 2015a). The most established process to produce DGP is prehydrolysis kraft (PHK), which combines acidic prehydrolysis to extract hemicelluloses followed by kraft cooking for lignin removal (Young 1994; Sixta 2006; Ibarra *et al.* 2010; Lahnalammi *et al.* 2018; Chen *et al.* 2022; Areej *et al.* 2023). Another major method is the acid sulfite (AS) process, which uses sulfurous acid or bisulfite to simultaneously solubilize lignin and hemicelluloses, producing highly reactive pulps ideal for cellulose derivatives like acetate and ethers (Warsta and Vourinen 2013; Duan *et al.* 2015a; Bajpai 2018a; Fiskari *et al.* 2021; Tao *et* *al.* 2022). Modified sulfite processes, particularly those employing magnesium or sodium based, allow for more controlled cooking and improved chemical recovery, making them suitable for specialty and pharmaceutical-grade pulps (Annergren and Germgard 2014).

Lastly, organosolv and hybrid pulping strategies—which integrate organic solvents, alkaline or oxidative pretreatments, and enzymatic hemicellulose removal—are emerging alternatives aimed at expanding raw material diversity (including non-wood and recycled sources), improving sustainability, and enhancing resource efficiency (Zhao *et al.* 2009; Iakovlev *et al.* 2009; 2014; Vera *et al.* 2023). Nonetheless, these technologies currently face limitations in commercial-scale-up, technical integration, and economic viability (Bajpai 2014a). Table 1 summarizes pulping processes and their advantages for developing the characteristics of DGP.

Table 1. DGP Production Processes: Chemical Reactions and Fiber Composition

Process	Main Reactions	Raw Materials	Alpha-Cellulose	Hemicellulose Removal	Lignin Removal	Fiber Strength
Prehydrolysis Kraft (PHK)	Acid hydrolysis + Alkaline	Hardwoods, Softwoods	High	High	High	High
Acid Sulfite (AS)	Acidic sulfonation	Mainly Hardwoods	Very High	High	High	Moderate
Modified Sulfite	Controlled sulfonation	Various	High to Very High	High	High	Moderate to High
Organosolv / Hybrid	Solvolysis + Hydrolysis	Non-woods, agro-waste	Medium–High	Medium–High	Medium	Variable

RAW MATERIALS AS FEEDSTOCK FOR DGP PRODUCTION

Wood remains the primary feedstock for dissolving grade pulp (DGP) production because of its high cellulose content and well-established processing technologies (Warren 2025). Both hardwoods and softwoods are used, with their differences in fiber morphology and chemical composition influencing pulping performance and final pulp quality (Su *et al.* 2018; Li *et al.* 2023).

Hardwoods, such as eucalyptus, birch, and maple, generally contain less lignin and shorter fibers, allowing for bleaching and the production of high-purity pulps to be achieved under milder processing conditions (Hertzberg 2019; Quintana *et al.* 2024). In contrast, softwoods—particularly species such as *Pinus*, *Picea*, *Larix*, *Cedrus*, and *Tsuga*— produce stronger pulps due to their longer fibers but require more intensive pulping and bleaching because of their higher lignin and hemicellulose contents (Chen *et al.* 2016).

Alternative lignocellulosic feedstocks, including bamboo, cotton linters, and agricultural residues, have attracted increasing interest due to their availability and sustainability advantages (Matin *et al.* 2015; Harsono *et al.* 2016; Huang *et al.* 2019;

Plakantonaki *et al.* 2025; Wojtasz *et al.* 2025). Bamboo is a rapidly renewable resource with favorable fiber properties but may contain high silica levels that complicate pulping (Sixta *et al.* 2013; Sugesty *et al.* 2015). Cotton linters provide exceptionally high α-cellulose content and low lignin, making them ideal for high-purity DGP. However, their cost and limited availability restrict large-scale use (Balkissoon *et al.* 2023; Frazier *et al.* 2024b). Agricultural residues, such as sugarcane bagasse, wheat straw, and corn stalks, represent abundant, low-cost feedstocks, but their higher ash, silica, and hemicellulose contents require tailored pretreatment and bleaching strategies (Abou-State *et al.* 1988; Behnin and Zeyghami 2009; Freitas and Colodette 2014; Matin *et al.* 2015; Chen *et al.* 2016; Urdaneta *et al.* 2024).

As shown in Fig. 5, softwood is the dominant feedstock for DGP production, accounting for approximately 72% of global DGP production capacity (Balkissoon *et al.* 2023). Cotton linters contribute roughly 10%, while hardwoods make up about 13%. This latter category also includes non-wood lignocellulosic materials such as bamboo, bagasse, and hemp (Sugesty *et al.* 2015; Balkissoon *et al.* 2023; Vera *et al.* 2023; Frazier *et al.* 2024b; Quintana *et al.* 2024).

PGP and recycled fibers have also emerged as promising alternative feedstocks, driven by sustainability goals and the growing demand for regenerated cellulose (Janzon *et al.* 2008; Wang *et al.* 2014; Ghahrani *et al.* 2023; Gong *et al.* 2023; Damaceno *et al.* 2024). Kraft pulps, recovered paper, and other cellulose-rich waste streams can be upgraded to DGP through chemical and enzymatic treatments that remove hemicelluloses, residual lignin, fillers, inks, and other contaminants, thereby increasing α-cellulose content and pulp reactivity (Geffertova and Geffert 2012; Asikainen *et al.* 2014; Kumar and Christopher 2017; Chacon *et al.* 2022; Cunha and Simões 2023; Gong *et al.* 2023; Magahlães de Oliveira *et al.* 2023; Damaceno *et al.* 2024). Common upgrading methods include cold caustic extraction, alkaline or acid purification, bleaching, and enzymatic treatments targeting selective hemicellulose removal while preserving cellulose integrity (Jackson *et al.* 1998; Wang *et al.* 2014; Jahan *et al.* 2016; Tian *et al.* 2016).

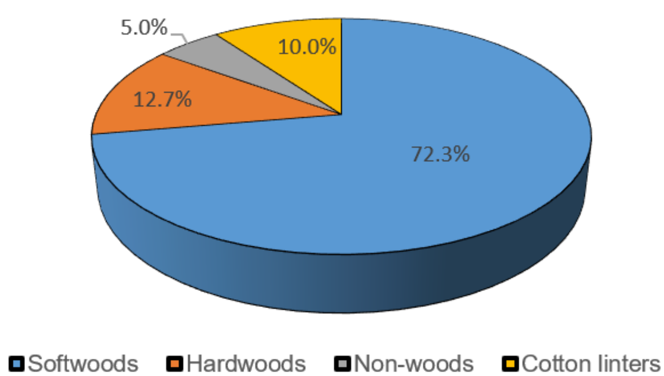

Fig. 5. Raw materials distribution used for DGP production

Table 2 summarizes the approaches reported in the literature that demonstrate the technical feasibility of converting lower-value paper-grade and recycled fibers into DGP. A thorough understanding of fiber morphology is essential for assessing the suitability of recycled fibers as feedstocks for DGP production.

Table 2. Summary of Scientific Investigations into Upgrading PGP and Waste Paper to DGP

No.	Feedstock	Main Process / Approach	End Use	α-cellulose (%)	Reactivity / Alkali Solubility	Intrinsic Viscosity	Reference
1	Mixed recovered paper; newspapers, magazines	Alkaline purification and bleaching	Viscose	55.1 → 83.0	**Fock reactivity:** 45.6 → 84.1%	669 → 351 - 479 mL/g	(Damaceno *et al.* 2024)
2	Bleached softwood kraft pulp (BSKP)	Alkaline extraction	DGP general	86.32 → 90.21 – 97.57	S10: 5.44 → 1.67 – 4.89%	742 → 700 – 758 mL/g	(Gong *et al.* 2017)
3	Bleached softwood Kraft pulp (BSKP)	Chemical and enzymatic upgrading	Lyoncell	85.5 → 89.6 – 90.6	S10:14.5 →10.4 – 9.4%; S18:13.5 → 9.1 – 8,4%	699 → 430–468 mL/g	(Gong *et al.* 2023).
4	Old corrugated containers (OCC)	Chemical purification and bleaching	Viscose	55.0 → 90.5	**Fock reactivity:** 53.13 → 85.67%	**Degree of polymerization (DP):** 1361.5 → 913.4	(Ghahrani *et al. 2023)*
5	Bleached softwood Kraft pulp (BSKP)	Cold caustic extraction	DGP general	84.2 → 97.1	S10: 12.2 →2.0% S18: 11.9 →2.3%	965 → 1,007 mL/g	(Tian *et al.* 2016)
6	Paper grade bleached hardwood Kraft pulp (BHKP)	γ-Valerolactone (GVL) treatment extraction; 60%, 120 °C, 2 h	Viscose	82.5 → 89.2 - 92.3	**Fock reactivity:** 40.1 → 54.6%	658 → 595 mL/g	(Liu *et al.* 2024)
7	Bleached softwood Kraft pulp (BSKP)	Enzymatic + alkaline peroxide treatments	Viscose	86.0 → 92.1	**Fock reactivity:** 32.4 → 68.7%	875.0 → 506.9 mL/g	(Wang *et al.* 2014)
8	Paper-grade rice straw pulp	Alkaline extraction and bleaching	Viscose	88.2 → 91.3	**Fock reactivity:** 13.8 →68.7% S10: 18.5 → 16.2%; S18: 12.4→ 8.6%	4.86 → 2.33 mPa.s	(Sharmin *et al.* 2025)
9	Paper grade bleached hardwood Kraft pulp (BHKP)	Enzymatic and alkali extraction treatments	Viscose	83.3 → 91.6 – 98.2	S10: 9.0% → 4.6 – 1.2%; S18: 6.7% →1.4 – 0.8%	19.7 →3.6 – 17.1 cP	(Jackson *et al.* 1998)
10	Old corrugated cardboard (OCC) wastepaper	Formic acid delignification + alkaline extraction + bleaching	Viscose / Rayon	72.2 → 94.7-	**Fock reactivity:** 60.2%; S10: 10.8%; S18: 5.8%	12.3 → 3.0 mPa.s	(Jahan *et al.*, 2016a)
11	White press (paper mill residual)	Acidification + alkaline extraction	Rayon	79.4 → 91.1	**Fock reactivity:** 68.8%; S10: 11.1%; S18: 7.6%	4.33 mPa.s	(Jahan *et al* 2016b)
12	ECF-bleached kraft pulp	Mechanical refining + 5.5% - 9% CCE + endoglucanase	DGP general	81.5 → 89.10 – 95.82	**Fock reactivity:** 46.7% → 23.0 – 81.0 %	628 → 402 – 711 mL/g	(Duan *et al.* 2016)

Differences between Wood, Paper Grade, and Waste Paper Pulps

The quality of recycled pulp is directly determined by the history of the fibers, including their origins and the processes and treatments they have undergone. McKinney (1995) identified five distinct stages in fiber history: fiber furnish and pulp history, papermaking process history, printing and converting history, consumer use and collection history, and recycling process history. Each stage results in cumulative chemical and morphological changes in the fibers (Fig. 6).

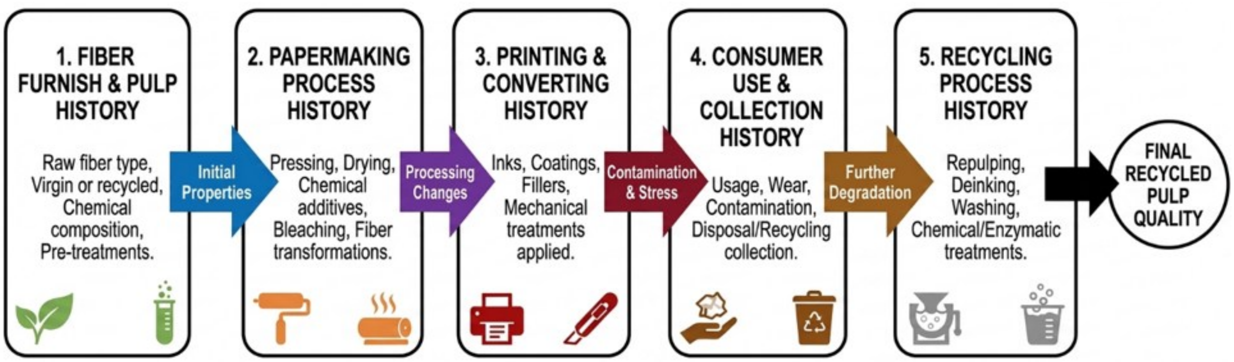

Fig. 6. Cumulative impact of fiber history on recycled pulp quality: stages and chemical-morphological changes

Comparison of Fiber Morphology

The principal morphological differences between virgin biomass fibers and waste paper pulps, as well as the effects of papermaking and recycling on fiber properties relevant to cellulose purification and reactivity, are found in Table 3.

Virgin pulps have typically longer and structurally intact fibers, particularly in softwoods, where fiber length strongly influences mechanical strength and network integrity (Biermann 1996; Bajpai 2018b; Jirarotepinyo *et al.* 2025; Lan *et al.* 2024). Fiber width is relatively uniform and species-dependent, with thick, well-preserved cell walls and an open lumen. External surfaces are smooth, and the primary wall remains intact, promoting high swelling capacity and strong inter-fiber bonding *via* abundant accessible hydroxyl groups (Stone and Scallan 1967; Ek *et al.* 2009). Hornification is largely absent prior to processing, allowing fibers to re-swell upon rehydration (Hashemzehi *et al.* 2024). Consequently, virgin pulps generally exhibit low fines content and low ash levels (Monte *et al.* 2009). In contrast, waste paper fibers display pronounced morphological degradation due to prior papermaking, usage, and recycling. Repeated mechanical handling, refining, pressing, drying, and rewetting cycles shorten fibers and increase curl and kink, while width becomes more variable and lumen tends to collapse as cell walls stiffen (Nazhad and Paszner 1994; Hubbe *et al.* 2007). Hornification intensifies with each drying–recycling cycle, resulting in irreversible hydrogen bonding within the fiber wall, reduced internal porosity, and diminished re-swelling capacity upon rehydration (Fernandes *et al.* 2004; Mo *et al.* 2022; 2024). Surface morphology is generally rougher and more damaged in recycled fibers, which can hinder uniform chemical reactions in subsequent processing steps. Recycled pulps also contain higher fines content and a greater burden of contaminants (inks, adhesives, coatings, fillers), contributing to elevated ash content (Brancato *et al.* 2007; Monte *et al.* 2009; Bajpai 2014b).

Table 3. Morphological Differences Between Virgin Biomass Fibers and Waste Paper Pulps

Morphological Feature	Virgin pulps	Waste paper Pulps	Papermaking effect	Recycling effect	References
Fiber Length	Long and intact	Shorter fibers	Slight reduction during refining	Further shortening from breakage and fatigue	(Biermann 1996; Małachowska *et al.* 2023a)
Fiber Width	Uniform, species-dependent	Variable width	Mostly unchanged	Reduced from collapse and hornification	(Hubbe *et al.* 2007; Ek *et al.* 2009)
Cell Wall Thickness	Thick, well-preserved	Thinner, degraded	Slight compression during pressing/drying	Rigid due to hornification	(Fernandes *et al.* 2004; Nazhad and Paszner 1994)
Fines Content	Low	High	Slight increase from refining	Increased fines generation due to fiber fibrillation and fragmentation	(Howard and Bichard 1992)
Curl and Kink	Low	High	Slight increase after drying	Strongly increased with cycling	(Małachowska *et al.* 2023b)
Surface Structure	Smooth, intact wall	Rough, damaged	Smoother after refining	Rougher, with ink/debris deposits	(Hubbe *et al.* 2003; Brancato *et al.* 2007)
Lumen (Fiber Cavity)	Open and well-defined	Collapsed	May stay open if hydrated	Collapses and resists reopening	(Stone and Scallan 1967)
Bonding Ability	High	Reduced	Strong in well-refined pulp	Weakened by hornification	(Stone and Scallan 1967)
Hornification	Minimal	Pronounced	Begins during drying	Worsens with each cycle	(Mo *et al.* 2022; 2024)
Fiber Swelling Capacity	High	Reduced	Slight loss after drying	Greatly reduced by hornification	Nazhad and Paszner 1994; Stone and Scallan 1967)
Contaminants Presence	Minimal	High (inks, fillers)	May increase with additives	Accumulates in mixed waste	(Bajpai 2014b; Herbert 2006; Monte *et al.* 2009)
Ash Content	Low	High	Depends on filler content	Increases with accumulated fillers	(Hubbe *et al.* 2007; Monte *et al.* 2009)
Brightness / Cleanliness	High (bleached)	Lower	Controlled by bleaching	Reduced by inks, coatings	General note

Papermaking Additive Residues in Waste Paper Fibers

Papermaking additives are essential for tailoring paper properties, improving brightness, printability, mechanical strength, opacity, and water resistance (Bajpai 2018b; Herbert 2006). Although these materials are not inherent constituents of lignocellulosic fibers, they become closely associated with fibers during paper manufacture and can substantially modify both fiber morphology and surface chemistry (Hubbe *et al.* 2007; Pivnenko *et al.* 2016). Common additives include mineral fillers, such as calcium carbonate, clay, and talc; sizing agents, including alkyl ketene dimer (AKD) and alkenyl succinic anhydride (ASA); surface coatings; retention aids; and dry- and wet-strength agents (Sixta 2006; Bajpai 2018b).

Many of these additives are intentionally designed to interact strongly with fiber surfaces. During papermaking, they may adsorb onto fibers, occupy pore spaces, or form surface films that modify the native hydrophilic character of cellulose. Sizing agents such as AKD and ASA react with or deposit on fiber surfaces, increasing hydrophobicity and improving water resistance by limiting liquid penetration into the sheet structure (Chen *et al.* 2019b).

Likewise, wet-strength resins such as polyamide-epichlorohydrin (PAE) enhance fiber-fiber bonding and improve the mechanical integrity of paper products (Fischer 1997). Because these additives exhibit strong affinity for cellulose, they are often only partially removed during conventional repulping and deinking operations and may continue to affect fiber properties, including surface charge, zeta potential, and wettability, throughout multiple recycling cycles (Chen *et al.* 2019b).

Mineral fillers, which are added to improve optical properties and surface quality, can also significantly influence fiber characteristics. Residual filler particles increase ash content and may partially cover reactive hydroxyl groups on cellulose surfaces, reducing fiber-fiber bonding potential and altering surface morphology (Monte *et al.* 2009). In addition, accumulated additives can affect fiber flexibility, swelling behavior, and pore structure. Surface deposits and filler particles may stiffen fiber walls, decreasing conformability and compressibility during sheet consolidation (Fischer *et al.* 2017). As a result, recycled pulps often exhibit increased bulk but reduced internal bond strength. Fine mineral particles may also obstruct fiber pores and capillaries, thereby modifying porosity and liquid transport properties that are important for printing and absorbency performance (Fortună *et al.* 2020).

The effects of papermaking additives often become more pronounced after repeated recycling. Recovered fibers frequently display rougher and more heterogeneous surfaces due to residual coatings, sizing agents, and incompletely removed deposits (Ganicz and Rózga-Wijas 2021). Additives may also contribute to higher fines content, either directly through the retention of mineral particles or indirectly by increasing fiber brittleness and susceptibility to fracture (Francolini *et al.* 2023). This embrittlement promotes crack formation, fiber fragmentation, and fines generation during repulping and refining operations (Hubbe *et al.* 2007).

Chemical Composition Differences

The chemical composition of recovered fibers varies significantly, depending on the original PGP (Nikparvar *et al.* 2025). For instance, when waste white paper-grade materials are used, delignification is not required; only the removal of contaminants and hemicelluloses is necessary to meet DGP specifications (Loureiro *et al.* 2021). In contrast, unbleached kraft pulps, such as OCC and/or double-lined kraft (DLK) – a cleaner unbleached waste paper grade than OCC – will require substantial lignin removal to be suitable for DGP applications.

These pulps represent approximately 30% of global chemical pulp production. They are primarily used in the manufacturing of wrapping and packaging materials, such as sack paper and paperboard for corrugated boards (Ek *et al.* 2009). Depending on the desired performance characteristics—such as printability or tensile strength —kraft liners can be produced in multiple layers with kappa numbers ranging from 55 to 110 and yields of 55% to 56%, as there must be a trade-off between lignin removal, pulp yield, and fiber quality (Biermann 1996; Ek *et al.* 2009). As a result, residual lignin, typically around 15% of the pulp, remains embedded within the fibers.

Virgin softwood exhibits notable differences from chemical pulps not only in the quantity but also in the structure of both native and residual lignin, as well as in its carbohydrate components, particularly hemicelluloses and lignin–carbohydrate complexes (LCCs) (Buchert *et al.* 1995; Henriksson *et al.* 2024). Importantly, the residual lignin present in unbleached kraft pulps is chemically distinct from native wood lignin. The kraft process induces substantial structural changes, including sulfidation (introduction of –SH groups), demethylation of aromatic methoxyl groups, and a reduction in β–O–4 ether linkages. Condensation reactions during pulping also increase the proportion of carbon–carbon (C–C) linkages, while simultaneously raising the content of phenolic hydroxyl groups—particularly in biphenyl and other condensed aromatic forms, and decreasing the content of aliphatic hydroxyl groups (Bouchard and Douek 1994; Mun *et al.* 2021).

Understanding these chemical and structural modifications is critical for tailoring pulp properties to specific applications, including post-processing steps such as subsequent delignification, bleaching, and the final conversion into DGP. These transformations arise from the kraft process itself, influenced by factors such as cooking temperature and time which together determine the characteristics of various unbleached kraft pulps, including high kappa number and bleachable-grade variants (Buchert *et al.* 1995; Ek *et al.* 2009; Rullifank *et al.* 2020; Henriksson *et al.* 2024).

Building on these chemical distinctions among virgin and waste paper, it is equally important to examine the major categories of recovered fibers, whose origin, usage history, and prior processing strongly influence their chemical and physical suitability for DGP production.

MAJOR GRADES OF RECOVERED FIBERS

Recovered paper is commercially classified into standardized grades, including OCC, ONP, OMG, MP, and SOP, based on fiber composition, contamination level, and intended end use (CEPI 2018; EN643 2014; ISRI 2026). These grading systems facilitate the segregation of recovered fiber streams according to their purity, strength properties, and compositional consistency, thereby improving recycling efficiency and maximizing the value recovered from secondary fiber resources (Rahman *et al.* 2014).

From the perspective of DGP production, the characteristics of each recovered paper grade largely determine its suitability as a feedstock and the extent of purification required. High-grade recovered papers, such as white press cuttings, DLK, pulp substitutes, and selected SOP grades, are generally considered the most attractive candidates because they contain relatively low levels of inks, coatings, fillers, and other contaminants (Pivnenko *et al.* 2014; 2016). In contrast, lower-grade recovered papers, including ONP, OMG, OCC, and other brown grades, typically contain higher concentrations of lignin, printing inks, mineral fillers, coatings, and papermaking additives, necessitating more intensive cleaning, deinking, bleaching, and purification treatments prior to conversion into DGP (Villanueva and Wenzel 2007). Similarly, SOP, bleached kraft papers, ledger papers, and pulp substitute grades generally contain more homogeneous fibers derived primarily from chemical pulps. Consequently, they can often satisfy DGP feedstock requirements after relatively moderate upgrading and purification processes (Sixta *et al.* 2013; Bajpai 2014b; Liu *et al.* 2016). By comparison, heterogeneous grades such as MP may contain a broad spectrum of fiber types, additives, and contaminants, posing additional challenges for process control and product consistency.

CONTAMINANTS IN WASTE PAPER RECYCLED AND THEIR REMOVAL

Although conventional recycling operations typically involve repulping, screening, contaminant removal, and bleaching, the production of DGP from recovered fibers requires substantially stricter control of residual non-cellulosic components, including inks, fillers, sizing agents, stickies, and other papermaking additives. These contaminants can adversely affect cellulose purity, accessibility, reactivity, and ultimately the quality of the final DGP product, making the development of effective purification strategies a critical requirement for recycled-fiber-based DGP production (Haworth 1977; Ek *et al.* 2009; Rahman *et al.* 2014).

The principal recovered paper grades according to the *Institute of Scrap Recycling Industries* (ISRI), and their relevant contaminants are summarized in Table 4. Together, these recovered fiber streams represent a significant and largely underutilized source of cellulose that could support both conventional paper recycling and the production of dissolving-grade pulp within a circular bioeconomy framework (Ozola *et al.* 2019).

Recovered waste papers contain both external macroscopic debris and internal chemical/microscopic impurities that compromise fiber quality, cellulose purity, and downstream process efficiency (Pivnenko *et al.* 2014; 2016). Contaminant removal strategies exploit differences in particle size, density, surface chemistry, and solubility through mechanical operations (screening, cleaning, flotation deinking) and chemical treatments tailored to specific waste paper grades and DGP specifications (Bouchette *et al.* 2022; Wang *et al.* 2023; 2024).

Physical separation techniques such as screening, hydrocyclone cleaning, and flotation deinking exploit differences in particle size, density, and hydrophobicity to remove metals, adhesives, inks, and extraneous materials from waste paper streams.

These mechanical operations effectively eliminate external contaminants—physically discrete, non-fibrous materials (*e.g.*, sand, glass, wires, plastics, metals) introduced during paper use, handling, and collection that remain as macroscopic particles during initial repulping (Rita *et al.* 1999; 2001; Chen *et al.* 2019b; Wang *et al.* 2023).

Internal contaminants, by contrast, integrate chemically with fiber structure or exist as colloidal/microscopic dispersions that resist simple mechanical separation (Vukoje and Rožić 2018). Soluble internal contaminants such as starch, alum, sizing agents, and dyes partially or fully dissolve during repulping, interacting with cellulose *via* hydrogen bonding and van der Waals forces, while charged species exhibit electrostatic attractions that promote re-deposition (Fig. 7 a and b) (Rita *et al.* 1999).

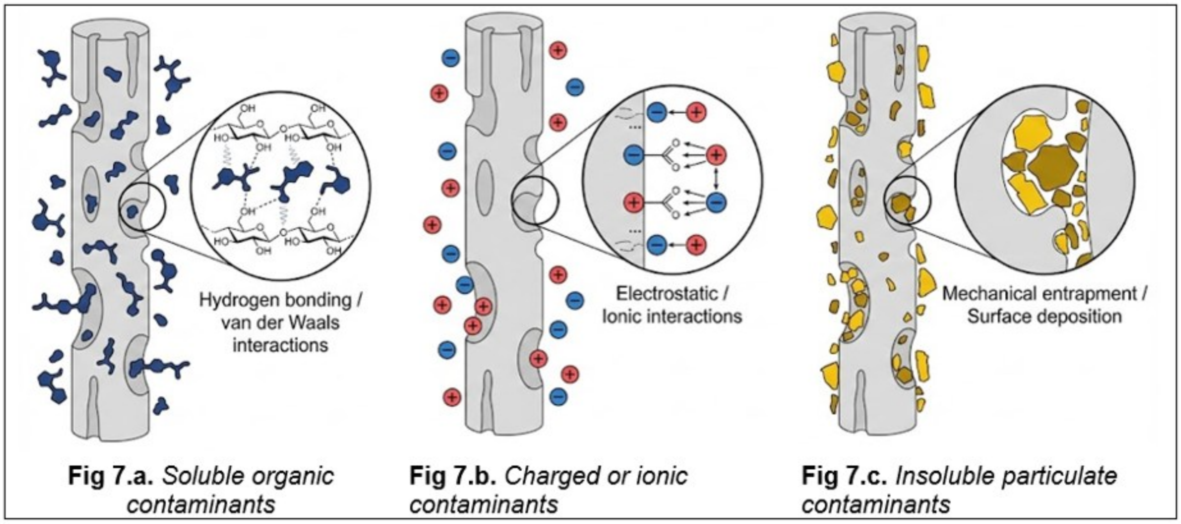

Fig. 7. Interaction mechanisms of contaminants in recovered cellulose fibers: Contaminants interact *via* (A) hydrogen and van der Waals forces for soluble organics, (B) electrostatic attractions for charged species, and (C) physical entrapment and deposition for insoluble particulates

Insoluble internal contaminants persist through physical entrapment and deposition mechanisms. A class called non-stickies (hydrophilic or neutral particles that disperse into suspension without adhering to equipment surfaces) form stable colloidal suspensions, whereas stickies (adhesive materials) adhere hydrophobically to equipment and fibers (Fig. 7.c), with behavior governed by temperature, dispersants, and surface chemistry (Licursi *et al.* 2016). Originating mainly from pressure-sensitive adhesives, hot-melts, labels, coating binders and tapes, these contaminants can persist in recycled pulp and impair purity, cellulose dissolution, filtration, and downstream DGP processing (Huber *et al.* 2018; Hubbe 2026). Their presence could elevate non-cellulosic impurities, accelerate equipment scaling, and cause filter plugging or un-dissolved residues during cellulose derivatization and dissolution (Chen *et al.* 2016; Pinto *et al* 2022).

Table 5 presents these established recovered fibers contaminant classification framework, which guides contaminant-specific removal strategies essential for achieving DGP purity requirements.

Table 4. ISRI Codes for Waste Paper Grades Originated from Graphics and Packaging Papers and Boards[1]

Code	Item	Description	DGP-relevant contaminants	
			Expected	Possible
04	Boxboard Cuttings	Clean, newly generated paperboard scraps produced during the manufacturing of folding cartons, rigid set-up boxes, and related boxboard products	Adhesives, mineral fillers, sizing agents, residual lignin (from kraft or recycled fibers)	Pigments, Inks
09	Over-Issue News (OIN) or Old newspapers (ONP)	Unused, surplus newspapers printed on newsprints, containing no more than the standard proportion of rotogravure and colored sections	Inks, mineral fillers	Staples, dirt/metal debris
10	Magazine (OMG)	Includes coated magazines, catalogs, and comparable printed materials, and may also contain a small proportion of uncoated, newsprint-style paper	Pigments, gloss additives, inks, adhesives, mineral fillers	Staples, dirt/metal debris
11 / 12	Old Corrugated Containers (OCC) / Double-sorted Old corrugated Containers (DS OCC)	Includes corrugated boxes made with liners composed of either test liner or kraft linerboard	Adhesives, inks, mineral fillers, residual lignin (from kraft fibers)	Tape, staples, dirt/metal debris
13	Double-Lined Kraft Corrugated (DLK)	Consists of new corrugated cuttings having liners of either test liner or kraft		
37	Sorted Office Paper (SOP)	Includes paper commonly produced in offices, made mostly of white and colored paper without groundwood, and containing no unbleached fibers	Inks, coatings, mineral fillers, staples, dirt, plastics, pigments, residual lignin (including mechanical pulp)	Adhesives, staples, paper clips, adhesives
54	Mixed Paper (MP)	Comprises all types of paper and paperboard of varying quality, regardless of fiber content, which have been sorted and processed at a recycling facility		
58	Sorted Clean News (SCN)	Comprises newspapers sorted from source-separated collection programs, converters, drop-off centers, and paper drives, including typical amounts of rotogravure, colored, and coated sections	Inks, mineral fillers, pigments	Adhesives, staples, dirt/metal debris

Note. Recycled Materials Industry (ReMA's ISRI) specifications for paper stock 2026; PS-2026. (ISRI 2026).

Table 5. Contaminants in Recovered Papers (adapted from Rita *et al.* 2001)

External	Internal		
	Soluble	Insoluble	
		Non stickies	Stickies
Sand	Starch	Plastic	Hot melts
Glass	Alum	Fillers	Wax
Wires	Soluble glue	Wet Strength	PSA
Golf balls	Sizing agent Dyes	Ink Pigments	Latex
Tapes	**Notes:**		
Wooden Boards			
Styrofoam	1.PSA = Pressure sensitive adhesives.		
Cans	2.Wax may or not be sticky. Depending on the temperature.		
Labels	3. Certain components of inks may be water soluble. Components may be sticky or no stickies.		

Repulping Overview and its Role in Recycling

Repulping is the first critical operation in waste paper recycling. Repulping is where recovered paper is disintegrated into individual fibers through mechanical and, when required, chemical action. This process releases inks, adhesives, fillers, and other contaminants, generating a fiber slurry for subsequent screening, cleaning, deinking, and purification (McKinney 1995). Repulping efficiency strongly influences fiber quality, contaminant removal, and the ability to achieve the high-purity cellulose required for DGP production (Bajpai 2014b, 2018b).

Low-consistency (LC) repulping (3 to 6% solids) enables efficient slurry handling and screening but requires high water consumption and may be less effective for removing strongly bound inks and wet-strength resins. In contrast, high-consistency (HC) repulping (8 to 18% solids) increases fiber–fiber friction, enhancing the detachment of inks, coatings, and adhesives while reducing water demand and preserving fiber quality (Forstall 2002). Under optimized conditions, repulping yields can exceed 80%, with losses mainly associated with coarse rejects and flakes (Ntifafa and Hart 2024).

Chemical-assisted repulping uses alkaline agents, hydrogen peroxide, surfactants, and dispersants to promote fiber swelling and contaminant release (Yilmaz *et al.* 2021). Table 6 summarizes representative conditions under which wet-strength resins can be removed through high-shear chemo-mechanical treatments conducted under controlled acidic or alkaline conditions, typically at temperatures exceeding 60 °C (Fischer 1997; Rita *et al.* 1999). Additional approaches, including enzymatic treatments and thermal or steam-assisted repulping, improve ink detachment, stickies removal, and adhesive softening while reducing chemical demand (Johnson and Pokora 1993; Herbert 1995; Fischer 1997; Rita *et al.* 1999).

Screening and Centrifugal Cleaning

Following repulping, screening and cleaning operations remove insoluble contaminants that negatively affect fiber quality and downstream purification efficiency (Rita *et al.* 2001).

Table 6. Wet Strength Resins and their Conditions (adapted from Rita *et al.* 1999)

Resin Class	Wet Strength	Type of curing	Estimated global wet-strength resin market share (based on PW Consulting 2025)	Repulping
Urea-formaldehyde (UF)	Permanent	Acidic	~12%	Oxidative alkaline treatment; using hypochlorite (NaOCl); pH ~9; ~70 °C; ~30 min, followed by mechanical pulping (Miller 1969; Staib 2005).
Melamine-formaldehyde (MF)	Permanent	Acidic	~5%	Oxidative treatment with hypochlorite; pH 4–10; 40–75 °C; 30–60 min, followed by mechanical repulping (Miller 1969; Aghmashhadi *et al.* 2021).
Polyamideamine–epichlorohydrin (PAE)	Permanent	Neutral/Alkaline	~65%	Acidic/oxidative followed by alkaline treatment; pH ~3–7 → 11; 70–90 °C; H_2O_2 or persulfate (Miller 1969; Herbert 1997; Chatrath and Durge 211; Ntifafa and Hart 2024).
Polyacrylamide glyoxal (GPAM)	Temporary	Neutral	~18%	Neutral to mildly alkaline; pH ~7–8.5; ~54–60 °C; mechanical repulping (Hagiopol *et al.* 2008).
Polyethyleneimine (PEI)	Temporary	Acidic/Alkaline	N/A — no reliable estimate identified	Neutral mechanical repulping; *e.g.*, pH 7, 50 °C; specific chemical/oxidative conditions not consistently reported (Staib 2005).
Polyvinyl amines (PVAm)	Temporary or permanent (depending on curing conditions	Acidic/Alkaline	N/A — no reliable estimate identified	Alkaline repulping; alkali-metal-containing caustic solution; carboxylate formation; mechanical dispersion. Specific pH and temperature not reported (Elton and Magnotta 1983; Xu *et al.* 2004; Mosutafa and Glover 2020).

These processes target external and internal impurities, including plastics, metals, sand, adhesives, and coarse stickies (Doshi and Dyer 2000; Blanco *et al.* 2007; Licursi *et al.* 2016; Hubbe 2026). Screening separates oversized contaminants from fiber suspensions using slotted or perforated screens, allowing fibers and smaller particles to continue through subsequent processing stages (Doshi and Dyer 2000; Forstall 2002; Fricker *et al.* 2007). Effective screening reduces reject content, protects equipment, and improves fiber uniformity for later purification steps (Herbert 2006).

Centrifugal cleaning complements screening by removing high-density contaminants such as grit, glass, and mineral fillers through differences in particle density. In hydrocyclone systems, rotational forces drive heavier particles toward the outer wall for rejection, while fibers remain in the accept stream (Olson and Rehmat 2001). In Fig. 8, multiple cleaning stages (coarse, medium, and fine) are commonly applied to progressively reduce contaminant levels according to feedstock characteristics (Herbert 2006; Sixta 2006; Bajpai 2014b; Yilmaz *et al.* 2021).

Deinking

After mechanical cleaning, deinking is essential for removing residual inks, chromophores, and fine hydrophobic contaminants such as microstickies, waxes, and hot melts (Wang *et al.* 2023). Deinking combines chemical and mechanical actions to detach ink particles from fiber surfaces, typically under alkaline conditions with surfactants or collectors that promote ink separation (Bajpai 2014b; Yang *et al.* 2022; Hubbe 2026).

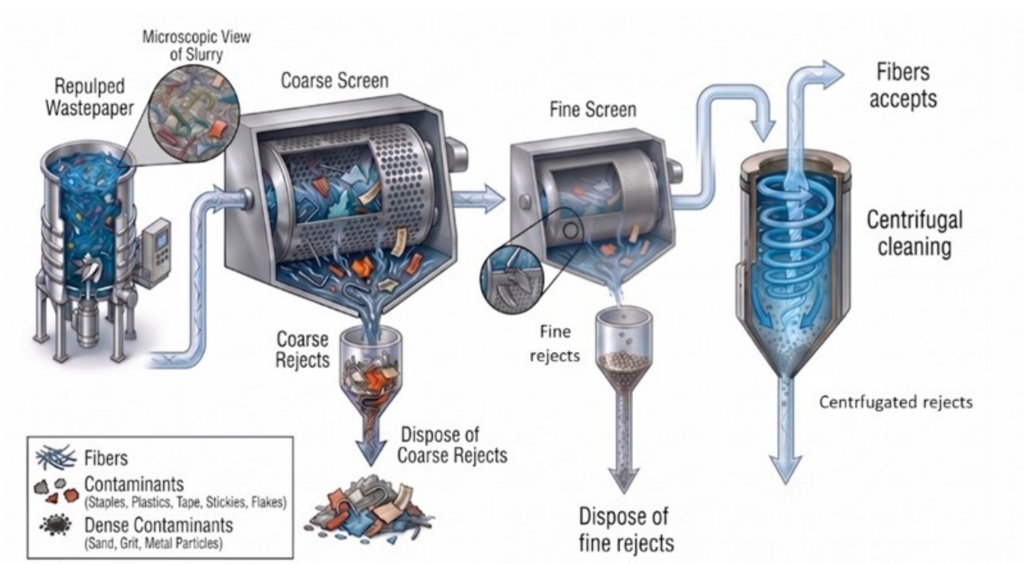

Fig. 8. Schematic diagram of cleaning and screening operations in wastepaper recycling

Flotation deinking is the dominant industrial approach, where air bubbles attach to detached ink particles and transport them to the surface for removal, improving pulp brightness and reducing ink specks (Fricker *et al.* 2007; Lee *et al.* 2011; Akbarpour *et al.* 2013; Chaiarrekij *et al.* 2000; Singh *et al.* 2020; Sulbarán-Rangel *et al.* 2020; Yang *et al.* 2022).

Enzymatic deinking, using cellulases, xylanases, and related enzymes, offers a lower-chemical-demand alternative by modifying fiber surfaces and improving ink release, although optimization for different wastepaper grades remains necessary (Pèlach *et al.* 2003; Singh *et al.* 2020; Ghanbarzadeh *et al.* 2021; Kumar and Dutt 2021).

Acid Washing for Advanced Contaminant Removal

Acid washing can provide an additional purification step to remove inorganic contaminants and metal ions that remain after conventional cleaning and screening (Kucbel *et al.* 2025). Through these treatments, mineral fillers, metallic oxides, and ash components could be dissolved, improving cellulose accessibility and reducing impurities that interfere with bleaching and derivatization (Phipps and Lorusso 2001; Jahan *et al.* 2016b; Pătrăucean-Patrașcu *et al.* 2025).

Mineral acids, such as sulfuric acid, can be used under controlled conditions to solubilize inorganic residues and reduce deposits that may affect subsequent processing (Jahan *et al.* 2016b). For recycled fibers, acid washing can decrease ash and metal content, increase α-cellulose purity, and improve the efficiency of subsequent alkaline extraction and bleaching stages (Fricker *et al.* 2007; Sixta *et al.* 2013; Yilmaz *et al.* 2021; Kucbel *et al.* 2025). However, thorough rinsing and neutralization are required to prevent residual acidity from affecting cellulose integrity or downstream operations (Hu *et al.* 2018; Martinsson *et al.* 2023).

Although not required for all recycled grades, selective acid washing is particularly beneficial for highly contaminated streams, supporting the production of high-purity cellulose suitable for dissolving pulp and other advanced applications (Potucek and Milichovsky 2000; Sixta 2006; Hubbe *et al.* 2007; Hart 2019).

BLEACHING FOR DGP PRODUCTION

Following repulping, screening, cleaning, and deinking, wastepaper-derived DGP requires intensive bleaching and purification to achieve the brightness, cellulose purity, and molecular integrity required for regenerated cellulose and derivative applications (Bodhlyera *et al.* 2015; Beltramino *et al.* 2018). Bleaching removes residual lignin chromophores and colored extractives, while subsequent purification targets hemicelluloses, ash, inks, and process additives that reduce cellulose reactivity and derivatization efficiency (Biermann 1996; Herbert 2006; Sixta 2006; Bajpai 2018b). Due to the higher variability and contaminant load of recycled fibers, tailored purification sequences are often required compared with virgin pulps (Buchert *et al.* 1995; Hosseinpour *et al.* 2014; Hart 2019).

Elemental Chlorine-free (ECF) and Totally Chlorine-free (TCF) Bleaching

ECF bleaching, based on chlorine dioxide (ClO_2), provides selective lignin oxidation with limited cellulose degradation and reduced formation of adsorbable organic halides (AOX) compared with conventional chlorine bleaching. Its balance between efficiency, pulp quality, and environmental performance has made it the dominant industrial bleaching technology (Biermann 1996; Sixta 2006; Hosseinpour *et al.* 2014; Fišerová *et al.* 2018; Bajpai 2018b; Hart 2019; Moyo *et al.* 2025).

TCF bleaching eliminates chlorine-containing chemicals and relies on oxygen-based oxidants such as O_2, H_2O_2, ozone, and organic peracids, thereby minimizing AOX formation and effluent toxicity (Sixta 2006; Sharma *et al.* 2020). However, its lower selectivity often requires more complex sequences, increasing chemical demand and the risk of cellulose oxidation (Fišerová *et al.* 2018; Potucek and Milichovsky 2000; Goto *et al.* 2023; Mailita *et al.* 2025). With optimized conditions, TCF processes can produce highly pure and reactive pulps while reducing environmental impacts (Bodhlyera *et al.* 2015; Llano *et al.* 2018; Métais and Germer 2019; Arce *et al.* 2020).

For wastepaper-based DGP, transition metal control is critical because Fe, Cu, and Mn from inks, pigments, and fillers can catalyze Fenton reactions during oxidative bleaching, generating radicals that accelerate cellulose degradation and reduce viscosity (Šelih *et al.* 2007; Koç *et al.* 2017; Huang *et al.* 2021; Martinsson *et al.* 2023). Acid washing, chelation with DTPA or EDTA, and effective interstage washing help minimize these effects and preserve cellulose integrity (Pinto *et al.* 2015; Goto *et al.* 2023).

Ultimately, both ECF and TCF sequences aim to maximize cellulose purity while maintaining polymer integrity. Their performance is often enhanced through complementary treatments such as alkaline extraction, cold caustic extraction (CCE), and ozone stages, which improve α-cellulose content, brightness, and reactivity through additional removal of hemicelluloses and inorganic impurities (Mozdyniewicz *et al.* 2013; Li *et al.* 2015; Tian *et al.* 2016).

HEMICELLULOSE REMOVAL

Hemicellulose reduction is essential in DGP production because residual xylan, mannan, and arabinan reduce α-cellulose content, restrict cellulose accessibility, and lower pulp reactivity by masking cellulose hydroxyl groups (Östberg *et al.* 2012; Strunk 2012; Li *et al.* 2018; Christoffersson *et al.* 2022). Their selective removal increases cellulose purity, brightness, and reactivity, which are critical for regenerated cellulose fibers and cellulose derivatives (FitzPatrick *et al.* 2010; Wollboldt *et al.* 2010; Roselli *et al.* 2014; Duan *et al.* 2015b, 2016; Wu *et al.* 2015; Palme *et al.* 2016; Vera *et al.* 2023; Frazier *et al.* 2024a).

CCE is the most established industrial method for hemicellulose removal. Typically conducted below 30 °C with 5 to 10% sodium hydroxide, CCE selectively dissolves hemicelluloses, particularly xylan, while largely preserving cellulose crystallinity and degree of polymerization, thereby increasing α-cellulose content and pulp reactivity (Puls *et al.* 2006; Schild *et al.* 2010; Mozdyniewicz *et al.* 2013; Li *et al.* 2015; Resende and Colodette 2015; Tian *et al.* 2016; Quintana *et al.* 2024; Ghahramani *et al.* 2025). Its main drawback is the generation of a highly alkaline spent liquor that is rich in dissolved hemicelluloses and residual NaOH, requiring efficient chemical recovery and wastewater management (Sixta 2006; Resende and Colodette 2015). Process sustainability can be improved through caustic recycling and recovery of dissolved hemicelluloses as value-added coproducts, although safe handling of concentrated alkali remains an important operational challenge (Thompson *et al.* 2001; Pokhrel and Viraraghavan 2004; Seyedin and Hassanzadeganroudsari 2008; Gong *et al.* 2017; Geng *et al.* 2020; Chen *et al.* 2021).

Enzymatic treatments using xylanases, mannanases, and arabinofuranosidases provide a selective and environmentally friendly alternative by hydrolyzing hemicelluloses under mild conditions, reducing chemical consumption and improving pulp reactivity (Christov and Prior 1993; Jackson *et al.* 1998; Ye and Farriol 2005; Gehmayr *et al.* 2011; Bajpai 2014a; Grönqvist *et al.* 2014; Wu *et al.* 2015; Duan *et al.* 2016; Kaur *et al.* 2024). Mechanical refining further enhances hemicellulose extraction by increasing fiber swelling and surface area, although excessive refining should be avoided because it reduces pulp viscosity and damages fiber structure (Grönqvist *et al.* 2014; Tian *et al.* 2014; Li *et al.* 2015; Duan *et al.* 2016).

PULP REACTIVITY ADJUSTMENT

High and consistent cellulose reactivity is essential for wastepaper-based dissolving pulps because it determines processability and product quality in regenerated cellulose fibers and cellulose derivatives (Östberg *et al.* 2012; Tian *et al.* 2013; Duan *et al.* 2017). As discussed above, compared with virgin wood pulps, recycled fibers are often hornified and exhibit lower hydroxyl accessibility, restricted reagent diffusion, heterogeneous molecular-weight distributions, and residual surface contaminants, all of which reduce derivatization efficiency (Zheng *et al.* 2024; Moser and Sjöstrand 2025).

To overcome these limitations, DGP production from waste paper should incorporate treatments that increase cellulose accessibility and improve reaction uniformity. Mild pre-hydrolysis or controlled depolymerization narrows the molecular-weight distribution and increases the proportion of accessible amorphous regions, enhancing alkali penetration and subsequent derivatization (Sango *et al.* 2018; Gondhalekar *et al.* 2019; Cunha and Simões 2023).

Likewise, fiber activation through alkaline conditioning, cold caustic extraction (CCE), or combined mechanical–chemical pretreatments promotes swelling and pore development, although excessive CCE or drying-induced hornification should be avoided because they reduce accessibility through fibril aggregation (Pönni *et al.* 2012; Resende and Colodette 2015; Li *et al.* 2015; Ghahramani *et al.* 2025).

Reactivity can be further improved by removing fines, fillers, inks, and other residual contaminants that block cellulose surfaces or consume derivatization reagents (Odabas *et al.* 2016). Bleaching and purification not only increase α-cellulose content by removing lignin and hemicellulose but also modify the fiber ultrastructure to facilitate reagent transport (Ao *et al.* 2025).

Enzymatic or mechano-enzymatic treatments provide an additional means of selectively removing hemicellulose and loosening fibrillar aggregates while largely preserving intrinsic viscosity (Köpcke 2008; Ibarra *et al.* 2010; Miao *et al.* 2015; Hutterer *et al.* 2017; Willberg-Keyriläinen *et al.* 2019; Ceccherini *et al.* 2021; Wu *et al.* 2026). Together, these complementary strategies (Fig. 9) enhance cellulose accessibility and reaction uniformity, enabling wastepaper-derived dissolving pulps to achieve reactivity comparable to conventional wood-based pulps (Wollboldt *et al.* 2010; Sixta *et al.* 2013; Resende and Colodette 2015; Rossi and Sole 2025).

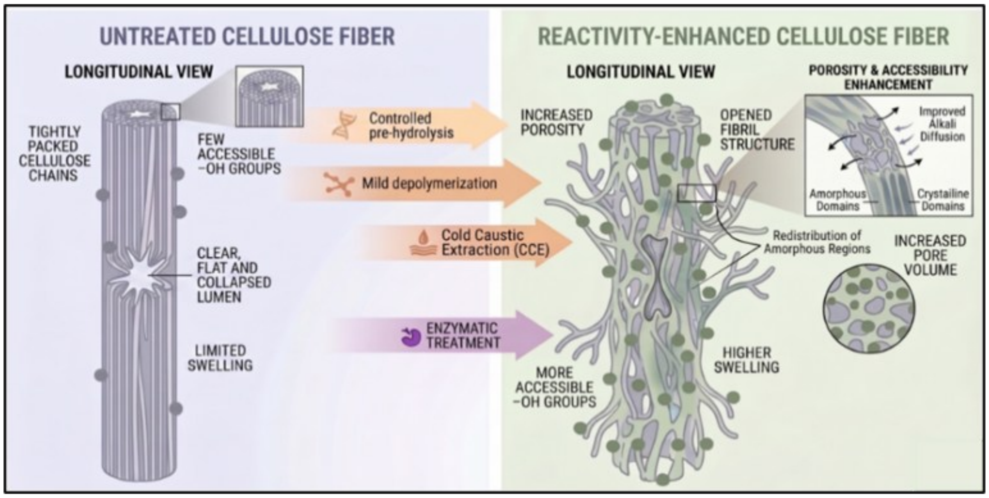

Fig. 9. Schematic representation of structural modifications enhancing the reactivity of dissolving pulp fibers

PROCESS FLOW PROPOSAL FOR DGP PRODUCTION FROM WASTEPAPER IN SECONDARY FIBER MILLS

Secondary fiber mills represent a potentially suitable platform for transformation into integrated DGP production facilities, leveraging their existing repulping, cleaning, and refining infrastructure while adapting advanced chemical and enzymatic upgrading technologies. The following section presents three scalable process flow strategies—tailored to different wastepaper grades and mill configurations—that aim to progressively remove contaminants, lignin, hemicellulose, and impurities while achieving the high α-cellulose purity (>93%), controlled viscosity, and reactivity required for viscose, lyocell, and acetate applications. These flows integrate feedstock sorting from *Material Recovery Facilities* (MRF).

Feedstock Classification, Repulping and Screening

Wastepaper from MRF is first classified into three primary streams based on ISRI grades (ISRI 2026), and lignin content. This is just like the philosophy of waste paper sorting (Rahman *et al.* 2014).

1st stream: *High-grade whites (09 ONP, 10 OMG, 37 SOP and 58 SCN:* Low lignin, printing inks/coatings, high ash content.

2nd stream: *Brown grades (04 Boxboard cuttings,11 OCC, 12 DS OCC and 13 DLK):* High lignin (4-8% residual), minimal inks.

3rd stream: *Mixed paper (54 MP):* Residual lignin, printing inks, high ash content.

Chemical-assisted repulping at alkaline conditions can use NaOH (1 to 2%, 45 to 55 °C) to remove internal soluble contaminants and to liberate fibers and disperse stickies/inks.

The repulped slurry is then subjected to coarse (>1.5 mm) and fine screening to remove external large non-fibrous contaminants such as plastics particles, metals (aluminum), and debris, followed by forward/backward centrifugal cleaning to eliminate both internal insoluble high-density (sand, glass) and low-density (small plastic particles, stickies) impurities.

Internal insoluble Contaminants Removal

After initial cleaning, acid washing is applied using sulfuric acid (H_2SO_4) at pH 2 and 70 °C, following the conditions reported by Jahan *et al.* (2016b), to remove entrapped inorganic contaminants such as $CaCO_3$, clay, and metal ions (Fe^{3+}, Mn^{2+}, Cu^{2+}) originating from pigments, dyes, and equipment. These metals can catalyze peroxide decomposition during TCF bleaching. Flotation deinking is selectively applied to streams 1 and 3, while brown grades proceed directly to delignification.

Delignification and Bleaching of Recovered Fibers

Brown-grade and mixed wastepaper streams require additional delignification to achieve the low lignin content required for DGP production. Oxygen delignification or mild soda/kraft treatments are used to reduce kappa number, followed by ECF or TCF bleaching sequences involving chlorine dioxide, alkaline extraction, oxygen, peroxide, or ozone to increase brightness and remove residual impurities.

Alpha Cellulose Enhancement and Reactivity Adjustment

To further improve pulp purity and increase the α-cellulose content of the processed pulps, from all the streams, hemicellulose content is reduced, either by CCE at high alkali concentration and room temperature or by enzymatic treatment with xylanases. Both approaches selectively remove hemicellulosic fractions while minimizing cellulose degradation. Following purification and chemical upgrading, cellulose reactivity is explicitly assessed using a standardized Fock reactivity test, providing a quantitative measure of alkali accessibility and reaction uniformity relevant for downstream derivatization (Tian *et al.* 2013). Because waste paper-derived pulps may exhibit variability in ultrastructure and molecular-weight distribution, this intermediate reactivity assessment enables targeted process control. Waste paper DGP might exhibit heterogeneous ultrastructure, requiring Fock reactivity assessment (target: 70 to 85% for viscose).

Low-reactivity pulps (<60%) receive endoglucanase treatment to loosen fibrillar regions and enhance alkali accessibility without excessive chain scission. After enzymatic adjustment, reactivity may be re-evaluated to confirm compliance with product specifications before proceeding to final finishing steps.

After final washing and thickening to remove residual chemicals, the pulp is dried and baled. The resulting DGP is characterized by high α-cellulose content, low hemicellulose and lignin levels, minimal ash content, controlled viscosity, and uniform, application-specific reactivity, making it suitable for downstream conversion into regenerated cellulose products. Accordingly, Table 7 summarizes the standard analytical methods used for DGP characterization. Fig. 10 provides a schematic representation of the arrangement of all stages involved in the DGP production process from wastepaper, as previously described.

Table 7. Key Quality Parameters and Application-specific Benchmarks for Dissolving-grade Pulp (Huang 1994; Sixta *et al.* 2013; Quintana *et al.* 2024)

DGP quality parameter	Standard / method	General target / relevance
α-Cellulose	TAPPI T 203	>90%; typically 92 to 94% for AS and up to 94 to 96% for PHK hardwood DGP
S10/S18	TAPPI T 235	Low alkali solubility; hemicellulose preferably <4%
Viscosity	TAPPI T 230	Generally ~400 to 600 mL/g for DGP; excessive viscosity reduces processability
Structural carbohydrates	NREL/TP-510-42618	High cellulose/glucose content and low hemicellulose
Fock reactivity	Fock test	≥50% desirable; >60% associated with high viscose production

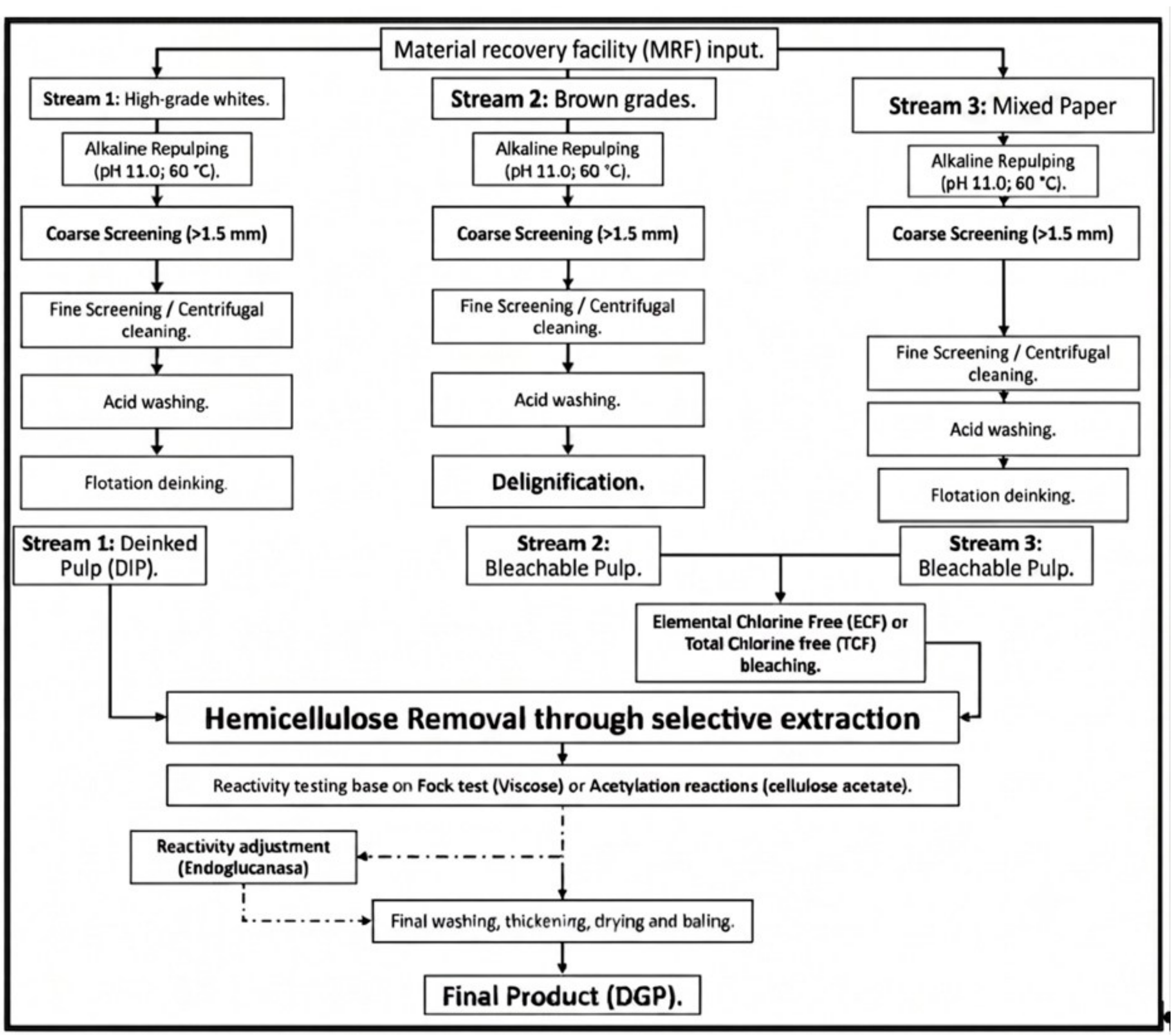

Fig. 10. Process flow for DGP production from wastepaper in secondary fiber mills

CONCLUSIONS

1. The transition from virgin wood-based dissolving pulp to recycled-fiber-derived dissolving grade pulp (DGP) is a strategic pathway toward greater circularity in the pulp and paper industry. This review provides a framework for upgrading secondary fibers using existing mill infrastructure and diverse recovered-paper streams.
2. Three differentiated processing strategies tailored to the specific characteristics of SOP, OCC, ON, OMG, MP as the most common waste paper types, including high-grade whites, and brown grades, might offer abundant secondary cellulose resources. Yet their conversion to DGP requires overcoming substantial technical challenges: fiber morphology degradation from multiple recycling cycles, elevated residual lignin (4 to 8% in brown grades), complex contaminants including stickies, polymeric laminates, ash-forming minerals (>10%), and printing inks and decreased reactivity.
3. To address constraints that come from recycled fibers, a sequence of targeted upgrading steps is required. First, intensified contaminant management—combining alkaline repulping, multi-stage screening, centrifugal cleaning, and, where necessary, acid washing—establishes a clean fiber base. Selective delignification and optimized bleaching strategies then reduce residual lignin from OCC and/or DLK feedstocks to the low kappa levels required for DGP applications. Hemicellulose removal is achieved through cold caustic extraction (8 to 10% NaOH, 25°C), possibly combined with refining-assisted xylanase treatment, enabling low molecular weight carbohydrate composition below 5% while maintaining intrinsic viscosity and preserving cellulose chain integrity. Finally, controlled endoglucanase post-treatment can homogenize fiber ultrastructure and enhance Fock reactivity, ensuring consistent performance in downstream viscose, lyocell, and cellulose acetate production.
4. Taken together, recycled-fiber-derived DGP represents a credible long-term strategy for high-value waste paper valorization and advancing circularity in the pulp and paper industry. However, variability in feedstock composition, fiber degradation, and contaminant content remains a principal limitation to achieving consistent DGP quality and performance.
5. Further research is needed to enable reliable industrial implementation, particularly in feedstock variability, contaminant management, process yield, chemical recovery, wastewater and sludge treatment, and product qualification. Techno-economic analyses, life-cycle assessments, and long-term mill-scale trials are also needed to validate the process under realistic industrial conditions.

List of Abbreviations

- **AKD:** Alkyl Ketene Dimer
- **AOX:** Adsorbable Organic Halides
- **APP:** Asia Pulp & Paper
- **AS:** Acid Sulfite
- **ASA:** Alkenyl Succinic Anhydride
- **BHKP:** Bleached Hardwood Kraft Pulp
- **BSKP:** Bleached Softwood Kraft Pulp
- **CCE:** Cold Caustic Extraction
- **CEN:** European Committee for Standardization (*Comité Européen de Normalisation*)
- **CEPI:** Confederation of European Paper Industries
- **CMC:** Carboxymethyl Cellulose
- **DGP:** Dissolving-Grade Pulp
- **DIP:** Deinked Pulp
- **DLK:** Double-Lined Kraft Corrugated
- **DMAc**: Dimethylacetamide
- **DP:** Degree of Polymerization
- **DS OCC:** Double-Sorted Old Corrugated Containers
- **DTPA:** Diethylene Triamine Pentaacetic Acid
- **EC:** Ethyl Cellulose
- **ECF:** Elemental Chlorine-Free
- **EDTA:** Ethylenediaminetetraacetic Acid
- **GPAM:** Polyacrylamide Glyoxal
- **GVL:** γ-Valerolactone
- **HC:** High-Consistency
- **HEC:** Hydroxyethyl Cellulose
- **HPC:** Hydroxypropyl Cellulose
- **ISRI:** Institute of Scrap Recycling Industries
- **LC:** Low-Consistency
- **LCC:** Lignin–Carbohydrate Complex
- **LCNC:** Lignocellulose Nanocrystal
- **MC:** Methyl Cellulose
- **MF:** Melamine-Formaldehyde
- **MP:** Mixed Paper
- **MRF:** Material Recovery Facility
- **NMMO:** N-Methylmorpholine N-oxide
- **OCC:** Old Corrugated Container
- **OIN:** Over-Issue News
- **OMG:** Old Magazine
- **ONP:** Old Newspaper
- **PAE / PAAE:** Polyamideamine-Epichlorohydrin / Polyamidoamine Epichlorohydrin
- **PEI:** Polyethyleneimine
- **PGP:** Paper-Grade Pulp
- **PHK:** Prehydrolysis Kraft
- **PSA:** Pressure Sensitive Adhesive
- **PVAm:** Polyvinyl Amine
- **ReMA:** Recycled Materials Industry Association
- **SCN:** Sorted Clean News
- **SOP:** Sorted Office Paper
- **TCF:** Totally Chlorine-Free
- **UF:** Urea-Formaldehyde
- **WoS:** Web of Science

ACKNOWLEDGEMENTS

The authors are deeply grateful to the reviewers and editors for their time, expertise, and constructive comments that greatly improved the quality and presentation of this manuscript.

Conflict of Interest

The authors declare that no conflict of interest exists with respect to the research, authorship, and publication of this article. All authors have read and approved the manuscript. The authors also certify that the manuscript contains original work, has not been published before, and is not being considered for publication by any other journal.

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Article submitted: July 23, 2026; Peer review completed: August 23, 2026; Revised version received and accepted: September 13, 2026; Published: September 22, 2026.
DOI: 10.15376/biores.21.4.Moran