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A REVIEW OF SURFACE COATINGS AND TREATMENT TRENDS IN DIGITAL PRINTING PAPER: SUSTAINABILITY AND INDUSTRY CHALLENGES

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Abstract

The rapid evolution of digital printing technologies has significantly transformed the landscape of printed media, driving demand for specially engineered paper grades tailored for high-performance applications. Unlike conventional offset printing, digital printing processes—such as inkjet, laser, and UV—require papers with enhanced surface characteristics to ensure optimal image quality, color vibrancy, ink adhesion, and durability. This review explores current trends in digital printing paper with a focus on surface treatments and coatings, which play a critical role in performance enhancement. Coatings such as pigment-based layers, polymer films, and functional chemical treatments have been developed to address the specific demands of different digital printing technologies. The paper also highlights emerging trends such as bio-based coatings, sustainable formulations, and recyclable substrates in response to increasing environmental concerns. Market-driven innovations, including synthetic printable papers, high-speed inkjet-compatible substrates, and specialized photo and label papers, are also discussed. The review concludes by outlining the challenges of cost-performance optimization and the need for standardization across the industry, along with a future outlook on the role of smart materials and sustainable chemistry in shaping the next generation of digital printing papers. Future research should focus on developing universal digital paper grades that balance high performance with recyclability and reduced environmental impact.

Keywords: Digital Printing, Paper Coatings, Inkjet Printing, Electrophotography, Sustainability

1. Introduction: The global printing industry is undergoing a paradigm shift, transitioning from conventional analog processes to highly adaptable digital printing solutions. This transformation is fuelled by the increasing demand for personalized, short-run, and on-demand printing across diverse sectors, including publishing, packaging, advertising, and textiles [1]. As digital printing technologies, particularly inkjet and laser, gain prominence, the paper industry faces the imperative to adapt and innovate.

Digital printing papers differ fundamentally from traditional printing substrates. While offset papers rely on ink transfer via plates and rollers, digital printing often involves the direct deposition of ink or toner, necessitating distinct surface properties. Crucial factors for achieving consistent print quality in digital systems include ink absorption rate, dot gain control, toner adhesion, and heat resistance. Consequently, paper manufacturers have developed a range of surface treatments and coatings, such as silica-based pigment coatings or polymeric layers, to optimize performance for specific printing methods.

In recent years, the focus has expanded beyond print performance to encompass sustainability, recyclability, and compliance with global environmental standards such as FSC, PEFC, and ISO 14001. Coatings and chemical formulations are being reengineered to reduce environmental impact while retaining print fidelity, particularly in applications like digital packaging, signage, and labels. As digital printing becomes a mainstream choice in both commercial and industrial applications, innovation in paper substrates, especially in terms of surface chemistry and functional coatings, continues to be a key area of research and development. This review aims to provide a comprehensive overview of the current state and future directions of digital printing paper, with particular emphasis on coating technologies and surface modifications. It also discusses sustainability considerations, market dynamics, and technological challenges associated with developing next-generation digital printing substrates.

2. Types of Digital Printing Technologies: Digital printing encompasses a variety of non-impact printing technologies that differ significantly in mechanism, ink application, and substrate compatibility. The choice of paper in digital printing is closely tied to the printing technology used, as each system imposes specific requirements on surface structure, ink absorption, and thermal or chemical resistance [2]. This section outlines the main types of digital printing technologies and their implications for paper design.

2.1 Inkjet Printing: Inkjet printing is one of the most widely used digital technologies, especially in commercial, textile, and wide-format applications. It operates by propelling tiny droplets of ink directly onto the paper surface. Inkjet systems are broadly categorized into two types: continuous inkjet (CIJ) and drop-on-demand (DOD). In both systems, surface treatment of paper plays a critical role.

Inkjet inks are typically water-based and require rapid absorption and immobilization to avoid feathering and color bleed. Coated papers with porous structures, such as silica- or kaolin-based coatings, are often used to control ink penetration and drying behavior. Additionally, ink-receptive layers with binders and cationic polymers can enhance image sharpness by fixing dye molecules on the surface.

2.2 Electrophotographic (Laser) Printing: Electrophotographic printing, also known as laser printing, uses a photoconductor drum to transfer dry toner onto paper, followed by fusing the toner via heat and pressure. This process demands paper with excellent dimensional stability, smoothness, and heat resistance. Papers designed for laser printing must resist curling and deformation under high temperatures (around 200°C) in the fuser unit. High-bulk or uncoated papers may not perform well due to toner offset or poor fusion. Therefore, specially treated or calendered papers are preferred for high-resolution applications. Smoother paper surfaces improve toner adhesion and reduce background noise.

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2.3 UV Inkjet Printing: UV printing utilizes ultraviolet light to instantly cure pigmented inks on the substrate surface. Unlike aqueous inkjet or laser printing, UV printing is less dependent on paper absorption, making it suitable for non-porous or coated substrates such as synthetic paper, film, or glossy coated sheets. Because UV inks remain on the surface, paper roughness and coating smoothness strongly influence print quality. Manufacturers are increasingly developing hybrid papers with top-coated layers compatible with both UV and water-based inks to support multifunctional printers.

2.4 Hybrid and Specialty Systems: Recent advancements have introduced hybrid digital systems combining inkjet with electrophotography or integrating digital stations into conventional presses. These require papers with multifunctional surface properties, capable of adapting to multiple ink types and printing passes. Moreover, textile digital printing, security printing, and direct-to-object applications are pushing paper innovation into niche areas where substrates must offer specific absorption profiles, flexibility, and durability.

Table 1: Paper Requirements for Each Digital Printing Technology

Printing Technology	Ink Type	Key Paper Requirements
Inkjet (aqueous)	Dye/Pigment	High absorbency, ink-receptive coating, smoothness
Laser (electrophotographic)	Dry toner	Heat resistance, dimensional stability, smooth surface
UV Inkjet	UV-curable ink	Surface uniformity, low absorbency, chemical resistance
Hybrid/Multisystem	Mixed	Versatility in coating, compatibility with multiple inks

3. Paper Requirements for Digital Printing: Digital printing systems impose unique demands on paper substrates due to the direct interaction of ink or toner with the surface. Unlike conventional printing, where intermediate steps such as plates and blankets are used, digital printing relies entirely on the substrate to support ink fixation, dot formation, and color fidelity. Therefore, achieving optimal print quality in digital systems requires careful engineering of paper properties, including surface structure, chemical composition, mechanical strength, and optical characteristics [3].

3.1 Surface Smoothness and Texture: Surface smoothness plays a critical role in determining image sharpness and uniformity. In laser and high-resolution inkjet printing, uneven surfaces can lead to toner or ink accumulation, streaking, and inconsistent image density. Papers intended for electrophotographic systems are often supercalendered or satin-finished to minimize surface roughness and improve toner adhesion. In inkjet systems, smoothness must be balanced with porosity to enable controlled ink absorption.

3.2 Ink Absorbency and Holdout: For inkjet papers, controlled absorbency is vital. If the ink penetrates too quickly, it may result in feathering and poor color density. Conversely, if absorption is too slow, drying time increases and may cause smudging or offsetting. Specialized ink-receptive coatings containing silica, calcium carbonate, or synthetic pigments are used to hold ink near the surface while allowing enough penetration for fixation. In UV printing, however, since the ink is cured on the surface, absorbency is less important, but surface energy and smoothness become crucial for adhesion and curing efficiency.

3.3 Optical Properties-Brightness, Opacity, and Gloss: Brightness affects the perceived vibrancy and contrast of printed colors. Digital papers are often manufactured to have high ISO brightness (>90%) using optical brightening agents (OBAs). Opacity prevents show-through in double-sided printing, which is especially important in thin papers for books and manuals. Fillers such as titanium dioxide or calcium carbonate are often added to enhance opacity. Gloss impacts the appearance and ink interaction. Glossy papers are preferred in photo printing and high-end brochures, while matte finishes are better for readability and minimal reflection.

3.4 Basis Weight and Caliper (GSM and Thickness): Digital presses have specific limitations for paper thickness. Therefore, basis weight (in GSM) and caliper (thickness) must align with machine specifications to avoid paper jams, misfeeds, or registration errors. Most digital papers fall in the range of 70–300 GSM, depending on application (e.g., flyers vs. packaging).

- Lightweight papers (70–90 GSM): Ideal for books and office printing.
- Medium weight (100–180 GSM): Used for brochures, inserts, and labels.
- Heavyweight (>200 GSM): Used for covers, cards, and packaging.

3.5 Dimensional Stability and Curl Resistance: Digital printing involves rapid changes in temperature and moisture exposure, especially in electrophotographic systems. Papers must remain dimensionally stable to avoid wrinkling, cockling, or curling, which can impair registration and cause mechanical failure during feeding. This is achieved by optimizing moisture content, fiber orientation, and coating uniformity.

Table 2: Summary of Key Paper Properties

Property	Importance in Digital Printing
Surface smoothness	Image sharpness, toner adhesion, print uniformity
Ink absorbency	Prevents feathering, improves drying time
Brightness	Affects color vibrancy and contrast
Opacity	Reduces show-through in duplex printing
Gloss	Enhances finish and image depth (for photo applications)
Basis weight & caliper	Machine compatibility and application-specific needs

Dimensional stability	Prevents curling and misfeeding in machines

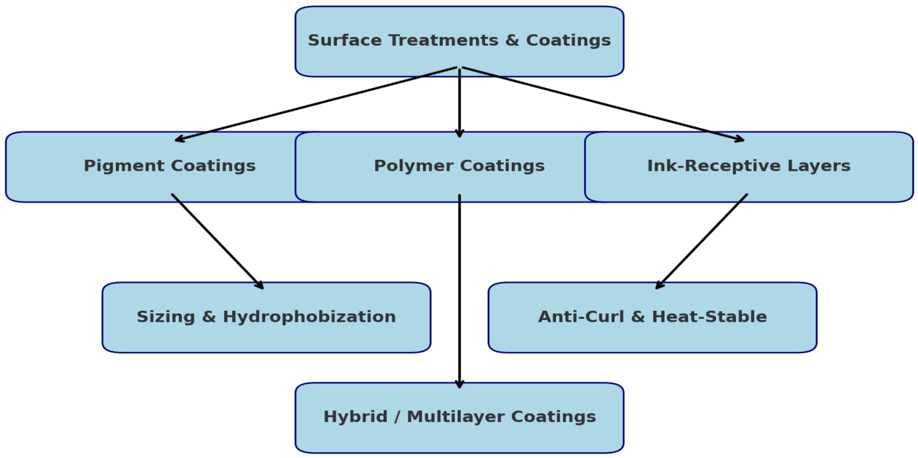

Figure 1: Overview of Surface Treatments and Coatings in Digital Printing Paper.

4. Surface Treatments and Coatings in Digital Printing Papers: Surface treatment and coating technologies are essential in defining the performance of digital printing papers. These modifications enhance ink adhesion, improve drying characteristics, control dot gain, and ensure compatibility with specific ink chemistries (e.g., aqueous, toner-based, UV-curable). This section provides a comprehensive overview of the most common coating strategies and their functional benefits in digital printing.

4.1 Pigment-Based Coatings: Pigment coatings form the foundation of many inkjet-compatible papers. These typically consist of inorganic particles such as precipitated calcium carbonate, silica, kaolin clay, or titanium dioxide, which create a porous surface that controls ink spread and absorption. Silica coatings are widely used in inkjet papers due to their high porosity and excellent ink absorbency. This porous structure acts like a microscopic sponge, rapidly drawing the liquid vehicle of the ink into the coating layer while leaving the solid pigment or dye particles concentrated on the surface. This mechanism prevents feathering and ensures sharp, vibrant images by minimizing ink spread [4]. Kaolin-based coatings offer smoother surfaces but lower absorbency, often blended with other pigments. Calcium carbonate provides brightness and opacity, particularly in coated matte papers. These pigments are combined with binders to control coating strength, smoothness, and adhesion. Pigment coating formulations must be tailored to balance ink absorption with holdout, ensuring fast drying without sacrificing print density. For instance, high-performance silica-coated inkjet papers designed for graphic arts applications commonly achieve color gamut volumes up to 10–15% higher than uncoated papers, alongside ink optical densities (OD) of 1.4 to 1.6 for black ink [5], ensuring deep blacks and vibrant colors. Similarly, papers using finely precipitated calcium carbonate (PCC) in their coatings can exhibit brightness levels exceeding 95 ISO and achieve print gloss values in the range of 30-40 GU (Gloss Units) at 75°, making them ideal for high-quality matte and satin finishes.

4.2 Polymer Coatings: Polymeric coatings enhance surface strength, flexibility, and chemical resistance. Commonly used polymers include:

- Polyvinyl alcohol (PVOH): Known for its ink holdout and barrier properties.
- Latex emulsions: Improve binding strength and surface smoothness.
- Acrylics and styrene-acrylics: Provide gloss and printability for premium-grade papers.
- Polyethylene (PE): Used in extrusion coating to make photo paper or water-resistant substrates.

These coatings are particularly important for photo-quality prints and high-speed inkjet systems where controlled ink immobilization is critical.

4.3 Ink-Receptive Layers (Precoats/Primers): Some papers, especially those used in industrial inkjet presses, are pre-treated with a cationic ink-receptive layer. These primers:

- Interact with anionic dye molecules to prevent ink penetration. These primers typically contain cationic (positively charged) polymers that electrostatically attract and bind with the anionic (negatively charged) dye molecules in aqueous inks [4]. This charge-based interaction effectively 'fixes' the dye onto or very near the surface, preventing lateral spread and enhancing color density and sharpness.
- Fix colorants near the surface, resulting in brighter, sharper images.
- Reduce drying time, especially for dye-based aqueous inks.

Such pre-treatment is vital for uncoated base papers used in on-demand publishing and transactional printing.

4.4 Multilayer and Hybrid Coatings: To meet the requirements of multifunctional printing systems, paper manufacturers often use multilayer coatings. For example, a base coating may control absorbency while a top layer adjusts gloss or toner adhesion. An example configuration includes a base pigment layer (e.g., silica + PVOH), an intermediate barrier or primer (e.g., cationic starch), and a top layer for gloss control or anti-curl properties. Hybrid coatings also allow for compatibility with both inkjet and electrophotographic systems, increasing flexibility in commercial print shops.

4.5 Surface Sizing and Hydrophobization: Surface sizing with agents such as starch, alkyl ketene dimer (AKD), or rosin enhances resistance to water and ink penetration. This is particularly important for duplex printing, where excessive absorbency can cause show-through or cockling. Sizing also contributes to ink holdout, surface strength, and curl resistance. Properly sized papers are better suited for both high-speed inkjet and laser printing where surface energy control is necessary.

4.6 Anti-Curl and Heat-Stable Coatings: Laser printing introduces thermal stress during fusing. To counter this, specialty coatings with anti-curling agents, plasticizers, or thermoplastic polymers are added. These allow the paper to remain flat and stable throughout the print cycle.

Table 3: Summary of Surface Treatment Functions

Coating Type	Functional Role in Digital Printing
Pigment Coatings	Ink control, fast drying, image sharpness
Polymer Coatings	Gloss, barrier properties, toner fusion
Ink-Receptive Layers	Ink fixation near surface, high color density
Surface Sizing	Water resistance, dimensional stability
Anti-curl Additives	Curl resistance in laser printing
Hybrid/Multilayer Coats	Versatility across digital platforms

5. Sustainability Trends in Digital Printing Paper: As environmental awareness and regulatory pressures increase globally, sustainability has become a central focus in the paper and printing industry. Digital printing, often promoted as a cleaner alternative to conventional methods due to reduced waste and chemical usage, still depends heavily on the sustainability of the substrates it uses. The lifecycle of digital printing papers, from raw material sourcing to recyclability, is now under close scrutiny. This section outlines the major trends shaping the future of eco-friendly digital printing papers [6].

5.1 Shift Toward Bio-Based Coatings: Conventional coatings often use petroleum-derived polymers (e.g., PE, acrylics), which pose recyclability challenges and contribute to plastic waste. In response, researchers and manufacturers are developing bio-based alternatives, such as:

- Starch derivatives and chitosan as binders and surface modifiers.
- Lignin-based coatings for barrier and ink-fixation functions.
- Soy protein and other biopolymers to replace synthetic latex in aqueous dispersions.

Bio-based coatings not only reduce carbon footprint but also enhance biodegradability and compostability of paper products [7]. For instance, replacing petroleum-derived polymers with bio-based alternatives like starch or lignin derivatives in coatings can reduce the carbon footprint associated with paper production by an estimated
15% to 25% per ton of coated paper [6]. Furthermore, certain bio-based coating formulations have demonstrated enhanced biodegradability, achieving over 60% degradation within 90 days under composting conditions, significantly improving the end-of-life profile of printed materials.

5.2 Deinkability and Recyclability: Digital printing poses unique challenges for paper recycling. Unlike offset inks that stay mostly on the surface, digital inks and toners can penetrate or fuse into fibers, complicating deinking. Key efforts to improve recyclability include:

- Using ink-receptive coatings that limit ink penetration.
- Designing toners and pigments with better deinking properties.
- Complying with INGEDE standards for deinkability evaluation (e.g., INGEDE Method 11) [8,9].

High-performance inkjet papers are now being developed with coatings that are fully repulpable and compatible with closed-loop recycling systems.

5.3 FSC and PEFC Certification: To ensure responsible sourcing, most digital printing papers now carry certifications such as FSC (Forest Stewardship

Council) and PEFC (Programme for the Endorsement of Forest Certification). These standards verify that the paper is made from sustainably managed forests, with traceability throughout the supply chain. Certifications are increasingly required by government contracts, publishing houses, and corporate clients.

5.4 Water and Energy Efficiency in Coating Processes: Advanced coating techniques like curtain coating and blade coating are being optimized to reduce water usage during production, minimize coating weight without compromising printability, and lower energy consumption during drying and calendaring. Some mills are even using on-machine coating systems to eliminate off-line processing, further reducing environmental impact. Advances in coating techniques, such as optimizing blade coating and implementing high-solids formulations, have led to a reduction in water consumption during the coating process by up to 20% [6]. Additionally, improved drying technologies, including infrared and hot-air impingement systems, have resulted in energy savings of 10-15% [6] in the coating drying phase compared to older methods, contributing to overall lower environmental impact in paper manufacturing.

5.5 Compliance with Global Ecolabels: Eco-labels such as EU Ecolabel, Blue Angel (Germany), and Green Seal (USA) now evaluate papers based on the absence of harmful chemicals (e.g., formaldehyde, optical brighteners), low VOC (volatile organic compounds) emissions from coating layers, and recyclability and compostability standards. Papers designed for digital printing are increasingly engineered to meet the criteria of these labels while maintaining high print performance.

Table 4: Summary of Sustainability Approaches

Sustainability Aspect	Key Strategies in Digital Printing Paper
Bio-based materials	Use of starch, lignin, proteins as coating components
Recyclability	Improved deinkability, repulpable coatings
Certified sourcing	FSC®, PEFC™, and chain-of-custody documentation
Energy & water efficiency	Optimized coating methods and reduced processing steps
Regulatory compliance	Meeting EU Ecolabel, Blue Angel, and Green Seal criteria

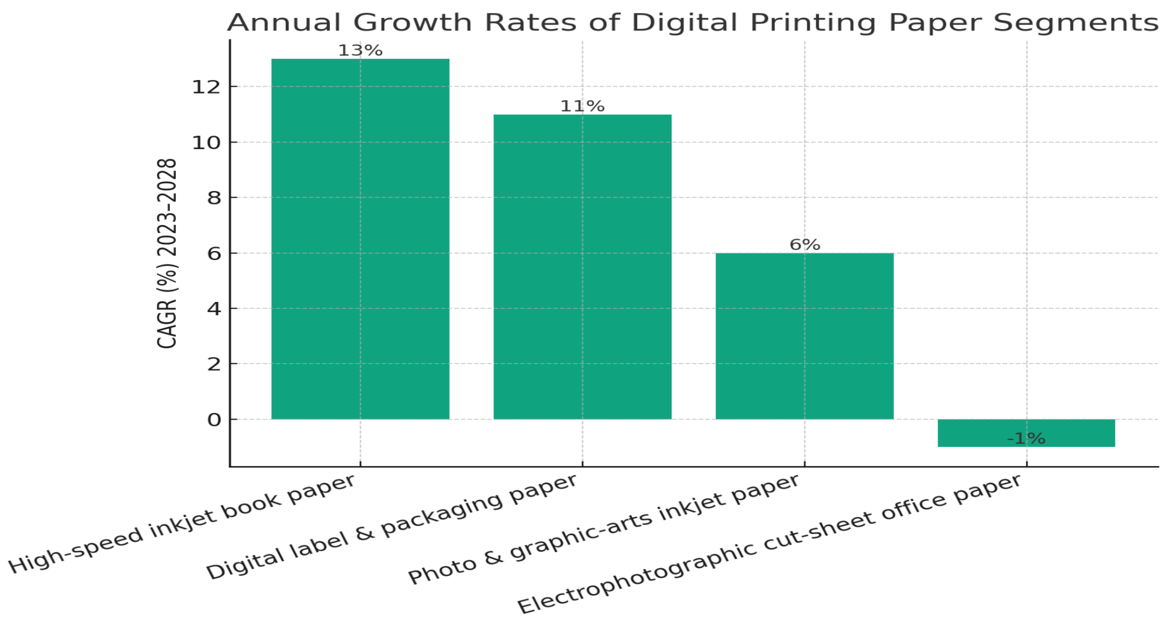

Figure 2: Annual Growth Rates (CAGR 2023–2028) of Key Digital Printing Paper Segments.

6. Market Trends and Innovations: The commercial success of any new digital printing paper ultimately depends on how well it addresses fast-evolving market needs [10]. Three converging forces are reshaping demand:

Table 5: Driving Forces and Their Impact on Paper Design

Driving Force	Impact on Paper Design
Rapid inkjet presses adoption (both sheet-fed and high-speed roll)	Higher run speeds require faster ink immobilization, flawless web transport, and resistance to cockle even at heavy coverage.
Brand demand for short, versioned, or personalized runs	Papers must deliver offset-like color fidelity on press runs as small as one copy, without post-print finishing delays.
Sustainability regulations & consumer scrutiny	Coatings must be de-inkable, bio-based, and certified, while still matching the look-and-feel brands expect.

Below are the most significant innovation vectors now visible in the market.

6.1 High-Speed Inkjet Compatible Grades: Instant-set nanoporous coatings (silica + PVOH blends) allow line speeds above 300 m/min with dye and pigment inks, enabling digital imprinting on catalogues and books previously printed offset. "HDI" (high-definition inkjet) papers combine high bulk with ultra-smooth surfaces, allowing publishers to switch seamlessly between offset and digital signatures in hybrid presses.

The latest generation of 'HDI' (high-definition inkjet) papers, for instance, are engineered to support press speeds exceeding 250 meters per minute, allowing for a 30% to 50% increase in throughput compared to earlier inkjet paper formulations [11]. These advancements enable resolutions of up to 1200 dpi with minimal dot gain (typically less than 5% at target optical density), effectively bridging the quality gap between digital and traditional offset printing for applications like books and direct mail.

6.2 Premium Photo & Graphic Arts Papers: Microporous PE-extrusion layers deliver lab-photo gloss while remaining tear-resistant; newer recipes replace part of the PE with bio-PE or PLA to aid recycling. Metallic-sheen inkjet papers embed aluminum flakes under a clear ink-receptive varnish, enabling designers to produce metallic spot colors without foiling. Premium photo papers featuring microporous PE-extrusion layers can achieve gloss levels typically ranging from 60 to 80 GU at 60° [12], providing a smooth, reflective surface akin to traditional silver halide prints. These substrates often boast immediate dry-to-touch times (less than 5 seconds) and demonstrate excellent water resistance, with ink run-off less than 2% after water droplet application.

6.3 Digital-Ready Packaging & Label Papers: The growth of e-commerce and personalized packaging fuels demand for inkjet-printable kraft and folding-boxboard [8]. Multi-layer barrier coatings provide grease and water resistance while keeping the outer surface ink-receptive [12]. Pressure-sensitive label stock now comes with dual-cure coatings so converters can print variable data by UV-inkjet, then over-laminate without smudge risk.

6.4 Synthetic & Hybrid Substrates: Mineral-filled polyolefin "paper" (60–80 % $CaCO_3$) provides tear and moisture resistance for outdoor signage and plant tags while running on standard inkjet presses [13]. Cellulose–polymer hybrids retain paper feel but withstand repeated folding for "smart-label" electronics.

6.5 Functional & Smart Papers: NFC-antenna and RFID-inlay papers integrate copper or graphene circuits during papermaking, avoiding separate tag application. Thermo-chromic coatings enable variable-temperature indicators on pharmaceutical packs, printable in a single digital pass.

Table 6: Snapshot of Annual Growth Rates (CAGR 2023-2028)

Segment	CAGR	Notes
High-speed inkjet book paper	13 %	Driven by on-demand textbook printing
Digital label & packaging paper	11 %	Personalized SKUs, regulatory QR codes
Photo & graphic-arts inkjet paper	6 %	Consumer photo books, luxury catalogues
Electrophotographic cut-sheet office paper	-1 %	Flat to declining; cannibalized by inkjet

7. Challenges and Future Outlook: Despite significant advancements, digital printing paper continues to face certain limitations and operational challenges:

- Coating Cost vs. Performance Trade-Offs: Enhanced coatings increase production costs. Balancing performance, cost-efficiency, and recyclability remains a key issue.
- Need for Standardization: The lack of universal performance standards for digital papers presents a significant challenge for both paper manufacturers and printers. This is exacerbated by the rapid evolution of digital press technologies and proprietary ink chemistries. While organizations like ISO (International Organization for Standardization) and industry consortia are working towards establishing benchmarks, the dynamic nature of the digital printing landscape makes comprehensive standardization a complex, ongoing effort.
- Integration with Industry: Smart printing and automated press setups require data-compatible substrates. Functional coatings and embedded indicators will be central to future innovation.

Key hurdles remain in balancing cost with ever-higher performance specifications, ensuring universal press compatibility, and meeting closed-loop recycling targets without sacrificing appearance. Breakthroughs are most likely in bio-polymer barrier layers, AI-optimized coating recipes, and papers pre-functionalized for printed electronics. Future research is likely to focus on developing universal digital paper grades, increasing compatibility, and improving lifecycle sustainability.

8. Conclusion: The digital printing revolution has sparked a wave of innovation in paper substrates, with a growing emphasis on coating technologies, sustainable formulations, and application-specific customization. Key trends include the development of inkjet-compatible coatings, recyclable materials, and smart substrates that support high-speed production and advanced image fidelity. Looking ahead, the industry is expected to integrate more environmentally responsible materials, address cost-performance challenges, and standardize paper specifications across platforms. As demand for on-demand, personalized, and digitally printed content continues to grow, the evolution of printing paper will remain a cornerstone of technological progress in the graphics and packaging sectors. Future research should emphasize the integration of biodegradable and multifunctional coatings, explore advanced deinking techniques for improved recyclability, and establish standardized testing protocols to ensure cross-platform compatibility of digital printing papers.

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Abbreviations
AKD: Alkyl Ketene Dimer
CAGR: Compound Annual Growth Rate
CIJ: Continuous Inkjet
DOD: Drop-on-Demand
DPI: Dots Per Inch
FSC: Forest Stewardship Council
GSM: Grams per Square Meter
GU: Gloss Units
HDI: High-Definition Inkjet
ISO: International Organization for Standardization
OBAs: Optical Brightening Agents
OD: Optical Density

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PCC: Precipitated Calcium Carbonate
PE: Polyethylene
PEFC: Programme for the Endorsement of Forest Certification
PLA: Polylactic Acid
PVOH: Polyvinyl Alcohol
UV: Ultraviolet
VOC: Volatile Organic Compounds

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