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MODERN DIGITAL PRINTING TECHNOLOGIES FOR PACKAGING MANUFACTURING: REVIEW AND PROSPECTS

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An overview of the current state of digital printing in the packaging industry is provided in the article. The key technologies (inkjet and electrophotographic printing), materials, and areas of application of digital printing systems in packaging manufacturing are examined. The advantages of digital printing – personalization, high production preparation speed, cost-efficiency for small print runs, and integration with smart technologies – are analyzed. The limitations and directions for further development are defined, in particular in the area of expanding compatibility with barrier and eco-materials.

Keywords: *digital printing, packaging, inkjet printing, personalization, short-run production, flexible packaging.*

Problem statement. The modern packaging industry is actively transforming under the influence of digitalization of production processes, the development of e-commerce, and the growing consumer demand for individualized goods. Packaging is no longer merely a protective shell of a product and becomes a carrier of information, emotional interaction, and brand marketing messages. Under these conditions, manufacturers face the need for rapid design updates, reduced time-to-market, and optimized printing preparation costs.

Traditional printing technologies, such as flexography and offset printing, remain dominant in mass production; however, they are less efficient for small and medium print runs, test batches, or localized advertising campaigns. The costs of manufacturing printing plates, the need for extensive preparation, and the risk of excess packaging stock limit production flexibility.

Digital printing, by contrast, opens new opportunities: design personalization, rapid production reconfiguration, economic feasibility of short series, and reduced waste during preparation. These advantages make digital printing a key technology for innovation in the packaging sector.

Growing demand for interactive and ecological solutions also stimulates the adoption of digital technologies that enable the use of QR codes, AR elements, supply-chain tracking tools, and product labeling aligned with sustainability standards.

Under such conditions, a systematic analysis of digital printing as a modern tool for producing packaging is relevant, including assessment of its functional and marketing capabilities, as well as identification of development prospects responding to market needs.

Research goal – to review and analyze modern digital printing technologies used in packaging manufacturing, determine their functional and marketing advantages, and outline prospects for technological development within the context of current industry needs.

Main research material. Packaging plays an important role in ensuring product quality preservation and attractiveness, forming the consumer's first impression, and influencing purchasing behavior. The modern consumer is oriented toward aesthetics, convenience, and personalized experience, which makes the use of advanced printing technologies in packaging production highly relevant.

According to research by several analytical companies [1, 2], the digital printing market in the packaging sector has shown dynamic growth in recent years. Its main drivers are:

- increasing importance of packaging as a marketing communication tool;
- rising demand for small print runs and quick design updates;
- growth of e-commerce and direct-to-consumer sales models;
- increasing role of product personalization

Digital printing technologies allow brands to adapt packaging design for specific markets, language groups, or promotional campaigns without significantly increasing production costs. This creates competitive advantages in the struggle for consumer attention both on store shelves and in online sales channels. Unlike traditional methods, digital printing makes it possible to reduce logistical risks associated with large packaging stockpiles, since production can match sales volumes precisely.

In packaging manufacturing today, two major groups of digital printing technologies are most widespread – inkjet and electrophotographic systems. Inkjet printing is gradually becoming the leading direction due to its versatility and ability to work with a wide variety of materials. In this process, finely dispersed drops of ink are directly applied to the substrate surface, ensuring high-quality reproduction of color images, photographs, and smooth gradients. This technology is particularly suitable for flexible and multilayer film substrates widely used in the packaging industry. The development of UV-LED inkjet systems provides additional advantages: instant ink curing enables printing even on low-absorbency surfaces such as metallized films or laminated materials [3].

Unlike inkjet printing, electrophotographic systems (toner technologies) use the principle of forming an image through electrostatic charge with subsequent thermal toner fixation. Their key advantages include stable color reproduction, high resolution, and image clarity – especially important when printing small fonts, technical markings and barcodes. Electrophotographic printing is most commonly applied to carton packaging, label production, and premium shell materials. However, one limitation of this technology is the difficulty of achieving proper adhesion on polymer substrates without special primers.

A separate niche in packaging production is occupied by hybrid lines that combine digital technologies with standard methods such as flexography. Such combinations allow packaging to be produced both in large print runs and with the option of integrating variable or personalized information in real time. This approach is highly effective for brands aiming to rapidly adapt product designs for local markets, promo campaigns, or various distribution channels without increasing prepress costs [4].

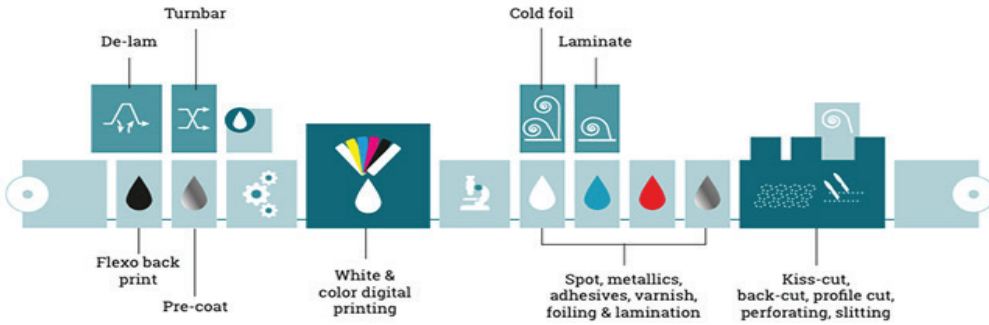

Fig. 1. Principles of operation of a hybrid printing line

The modern packaging industry is characterized by a significant diversity of materials to which digital printing technologies are applied. One of the most promising directions involves *flexible polymer materials*, particularly polypropylene, polyethylene terephthalate, and polyethylene films. These provide high barrier properties against moisture, oxygen, and external influences, which is critical for food and cosmetic products. However, working with such surfaces requires careful selection of inks and primers, since adhesion and print durability depend not only on substrate type but also on surface treatments such as corona discharge or the application of specialized functional coatings.

Paper and cardboard also occupy an important position in the digital printing market, as they are traditionally used in consumer packaging production – for cosmetics boxes, pharmaceuticals, confectionery, and other premium-segment items. These materials exhibit high compatibility with electrophotographic technologies, ensuring stable image quality and detail sharpness. Additionally, cardboard is a more eco-friendly and easily recyclable material, which becomes an added competitive advantage amid increasing demand for sustainable packaging solutions [5].

A separate category of materials for digital printing includes metallized surfaces, used for premium packaging and products with heightened requirements for aesthetic expressiveness. Such materials create additional challenges in ink adhesion and drying control; however, thanks to the development of UV-LED technologies, their effective use without loss of quality has become possible [6].

Environmental materials—recyclable polymers, biodegradable films, and paper with reduced synthetic content—are attracting increasing attention. Digital printing is especially relevant for such substrates because it helps minimize production waste and avoid packaging overproduction. Yet eco-materials often come with trade-offs in barrier

properties and mechanical stability, requiring further scientific research and engineering solutions [7].

In the medium-term outlook up to 2030, the packaging and digital printing market is showing substantial growth. For example, the digital printing packaging market is currently estimated at around USD 34 billion and is projected to reach approximately USD 56 billion by 2030 (about 10% annual growth) [1, 2]. Meanwhile, the market for "green" packaging – materials with improved recyclability, biodegradable components, and reduced synthetic content – is expected to grow from roughly USD 273 billion in 2023 to about USD 448 billion by 2030.

In other words, brands and packaging manufacturers will increasingly be guided not only by functionality and aesthetics but also by environmental characteristics – recyclability, carbon footprint, and circularity.

It is also interesting to predict what the landscape may look like by 2040. The aforementioned analytical reports warn: if current practices remain unchanged, by 2040 at least ≈29 million tons of polymers will enter the oceans annually. This creates strong motivation to transition toward a fully circular packaging economy – where packaging is designed for reuse, recycling, and waste minimization. Under such a scenario, by the 2040s we may see wide adoption of refillable containers and multi-cycle packaging solutions, as well as standardization of monomaterial packaging to simplify recycling.

The growing role of digital printing lies not only in enabling short runs and rapid design changes but also in its adaptability to circular and eco-models: for example, printing variable graphics for reusable containers, adjusting barrier or protective parameters on new biomaterials, or integrating digital identifiers directly into packaging.

Even more intriguing is the potential development after 2030 – toward the mid-2040s. Imagine a scenario where biodegradable films and polymers from renewable resources (such as PHA, PLA, or newly engineered chemically recyclable polymers) achieve cost competitiveness with traditional materials. Even today, scientific studies exist exploring AI-assisted design of new polymers with high barrier properties and chemical recyclability.

Under such conditions, packaging manufacturers may rethink their approaches: instead of "single-use" packaging, packaging becomes a service – multi-cycle solutions using digital printing for dynamic adaptation. For instance, packaging could be reconfigured (graphics, function, or purpose updated) through digital printing upon reuse or in support of new marketing campaigns. Additionally, by 2040 deeper integration of "smart packaging" technologies becomes feasible: printed sensors and microelectronics that monitor product or packaging condition could become widespread. For digital printing, this opens a new niche – not only printing graphics but also printing functional elements (conductors, sensors, adaptive surfaces).

Conclusion. Modern digital printing techniques – including inkjet, electrophotographic, and hybrid systems – provide extensive capabilities for adapting packaging to the specific needs of brands and markets, enabling high-quality reproduction of graphic elements and rapid design updates without substantial prepress costs. Their effectiveness largely depends on choosing appropriate materials, which include flexible polymer films, paper and cardboard, metallized surfaces, and environmentally oriented structures. The

interaction between technology and material determines key packaging parameters such as image durability, barrier properties, tactile characteristics, and recyclability. Therefore, optimizing this interaction is a decisive factor in the further development of digital printing in the packaging industry, ensuring a combination of functionality, aesthetic expressiveness, and compliance with sustainability requirements.

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СУЧАСНІ ТЕХНОЛОГІЇ ЦИФРОВОГО ДРУКУ ДЛЯ ВИГОТОВЛЕННЯ ПАКОВАНЬ: ОГЛЯД ТА ПЕРСПЕКТИВИ

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Сучасна пакувальна індустрія стрімко трансформується під впливом цифровізації виробничих процесів. За таких умов виробники стикаються з потребою швидкого оновлення дизайну, скорочення часу виходу продукту на ринок та оптимізації витрат на підготовку друку. Традиційні технології друку, такі як флексографія та офсетний друк, залишаються домінуючими у масовому виробництві. Проте вони є менш ефективними для малих і середніх накладів, пілотних партій чи локалізованих промокампаній. Витрати, пов'язані з виготовленням друкарських форм, необхідність тривалої підготовки та ризик надлишкового виробництва паковань обмежують гнучкість виробництва.

Цифровий друк, навпаки, відкриває нові можливості: персоналізацію дизайну, швидке переналаштування виробництва, економічну доцільність коротких серій та зменшення відходів під час підготовки. Ці переваги роблять цифровий друк ключовою технологією інновацій у галузі паковань.

У статті здійснено огляд сучасного стану цифрового друку в пакувальній індустрії. Розглянуто ключові технології (струменевий та електрофотографічний друк), матеріали та сфери застосування цифрових поліграфічних систем у виготовленні паковань. Проаналізовано переваги цифрового друку — персоналізація, висока швидкість підготовки виробництва, рентабельність малих накладів та інтеграція зі смарт-технологіями. Визначено обмеження та напрями подальшого розвитку, зокрема розширення сумісності з бар'єрними та екологічними матеріалами.

Ключові слова: *цифровий друк, паковання, струменевий друк, персоналізація, short-run, гнучкі паковання.*

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