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Benchmarking Color Reproduction Quality: A Comparative Study of Digital Printing Systems

ABSTRACT

The article investigates one of the key challenges of modern reproduction technology—the quality of color reproduction, the overall efficiency of printing production largely depending on its accuracy and predictability. The study employs a comprehensive empirical and theoretical approach based on the instrumental measurement of colorimetric parameters and chromatic coordinates of experimental prints produced on different output systems. These measurements were used for mathematical modeling and for determining the actual limits of the color gamut of the equipment. The obtained results demonstrate that the Indigo digital printing press provides the widest and most stable color gamut among the analyzed systems. To ensure a comprehensive technical and economic evaluation of the technologies, the article also presents experimental data on production time for different print-run volumes and graphical representations of printing efficiency. The analysis proves that, according to time-related criteria, digital printing systems are superior for short print runs, whereas conventional offset equipment remains the most appropriate and technologically justified solution for large-volume production.

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KEY WORDS
Quality of color reproduction, digital systems, color gamut

1. Introduction

The current stage of color science development is characterized by a transition from classical three-dimensional colorimetry to multi-channel spectral analysis and the prediction of print parameters using artificial intelligence techniques. Direct analysis of printing limits and ink synthesis stability requires studying the influence of the physicochemical properties of substrates and expanding conventional color reproduction models.

One of the fundamental problems of modern printing remains ensuring highly accurate and reliable color reproduction at the stage of transition from the screen original to the physical print. The complexity of solving this problem is due to the fundamental difference between additive color synthesis in monitors (RGB system) and subtractive synthesis in printing processes (CMYK system). To achieve the expected quality of the finished product, the end-to-end technological process requires a clear definition of the limiting colorimetric capabilities of specific printing equipment within the "print–substrate–ink" system. Even under conditions of precise production standardization, the actual technological process is always accompanied by random and systematic fluctuations, which necessitates the establishment, control, and quantitative assessment of technological tolerance values for color deviations.

In order for printing results to be predictable, the designer must clearly understand which colors a printing house is capable of reproducing and take this into account during the design process. It is important to realize that even with the highest quality of the finished product, certain tolerances always exist, and their magnitude must be considered.

In this context, print quality is understood as the accuracy of reproducing a specified color, as well as the possible variations between prints at different stages of the process, i.e., the stability and predictability of the result. High quality implies minimal tolerances; however, they will always be present, and it is impossible to eliminate them completely, as this is an objective reality. This determines the feasibility, relevance and scientific novelty of the presented work.

2. Literature review

The study by Blahová et al. (2025) focuses on the analysis of color reproduction variations in high-speed industrial inkjet printing systems using papers with different coating types. The authors demonstrate that the structure of the coated layer significantly affects the geometry of the color gamut. To extend these limits in modern packaging production, expanded multi-color printing technologies are increasingly employed, as described in detail by Green et al. (2024). Their research presents an extended colorimetric analysis of Expanded Color Gamut (ECG) printing and highlights the specific features of color profile generation beyond the standard CMYK process.

When complex secondary substrates such as recycled cardboard are used, where color stability is often limited, (Zhu et al., 2024) justify the application of machine-learning models for the real-time prediction of color deviations. This approach emphasizes the growing importance of automated quality control in contemporary pressroom environments.

The development of precise spectral prediction models is addressed in the study by Fan et al. (2025), which proposes a multi-channel prediction model for printed products based on HMSSA-BP neural networks. The authors demonstrate that intelligent optimization of weighting coefficients significantly reduces colorimetric errors in the CIELAB color space. This approach is consistent with the concept of preserving the color structure of high-resolution images proposed by Pan et al. (2022) through residual dense neural networks.

An important contribution to objective quality assessment is the metric introduced by Urban et al. (2023), which is based on the simulation of the Human Visual System (HVS) for spectral color reproduction analysis. This method enables consideration of the nonlinear nature of human color perception. Consequently, the standardization of quality parameters requires a comprehensive approach to the preparation of both traditional printed and modern electronic products.

In the works of Ukrainian scientific schools, in particular Senkivskyy et al. (2023), information technologies for producing high-quality visual content for newspaper publications have been developed, where color stability is limited by the properties of microporous substrates with low whiteness. In contrast, the conceptual foundations of multimedia content evaluation are addressed in Havenko et al. (2025), where a conceptual information technology model for the comprehensive assessment of electronic book publication quality is proposed. The transformation of color parameters in modern display systems is studied by Kao et al. (2025) using color electronic paper with front illumination (Color Electronic Paper) as an example, while algorithms for the mathematical restoration and correction of color characteristics on liquid crystal displays are investigated by Jia et al. (2018).

The issue of tonal reproduction of high dynamic range images using cone response functions of the human visual system based on the CAM16 color appearance model is addressed in Choi et al. (2019), which is essential for accurate cross-media visualization. A classification and comparative analysis of modern mathematical color models for efficient search and encoding of graphical content is provided in Shamoi et al. (2022). Digital compensation of geometric distortions and enhancement of color field resolution using generative adversarial networks (GANs) is presented in Kawabata et al. (2023). Multispectral analysis of microstructures using high-resolution 4K cameras for precise capture of color characteristics is demonstrated in (Kobayashi et al., 2023). Adaptive filtering and color balance correction in distorted environments are effectively addressed using two-domain fusion modules proposed in Cao et al. (2026). The visual reproduction of symbolic sign systems in media technologies is investigated in Li et al. (2019).

In the article (Mika et al., 2025), an in-depth comparative study between modern sheet-fed offset printing and premium digital presses (including HP Indigo liquid toner technology) is conducted. The authors focus on the analysis of color deviations using metric-based approaches and demonstrate that modern digital electrophotography is not only comparable to offset printing in plate reproduction accuracy but also provides a wider color gamut in the high-cyan and magenta regions due to the unique physicochemical properties of liquid toners.

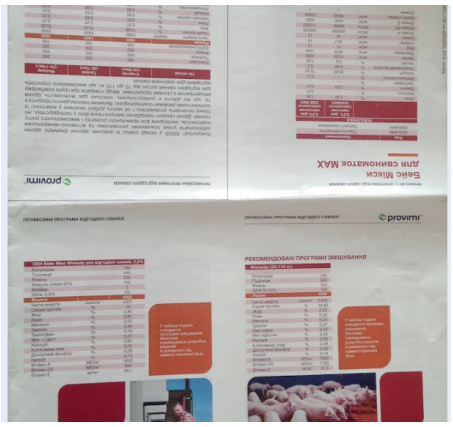
The work by García-Manrique et al. (2024) is directly related to the calculation and modeling of color volumes. The authors propose optimized algorithms for the rapid construction of ICC profiles of output devices by analyzing three-dimensional data arrays in the CIELAB space. They demonstrate that the combination of spectrophotometric control and mathematical approximation of print boundaries enables printing houses to dynamically reconfigure workflows (color workflows) in response to varying print run requirements without loss of colorimetric accuracy.

The study by Rovira et al. (2024) and Chen et al. (2024) addresses a topic that is critically important for this paper — technical and economic analysis and time-to-market. The researchers develop a mathematical model of production time that clearly differentiates efficiency zones of digital printing (where flexibility, fast setup, and the absence of plate-making processes dominate) and large-format offset systems (where high throughput compensates for prepress time). The authors determine the dynamic break-even point of print runs, which fully supports the analytical conclusions of this study and underlines its feasibility, relevance, and scientific novelty.

3. Research into the quality of color reproduction of digital and offset systems

At present, analog and offset color proofs in the printing industry have been almost completely replaced by digital color proofs, as the latter demonstrate excellent color reproduction while having significantly lower costs. Different monitors possess different color gamuts, and the same applies to printing on various types of substrates. For example, a color that can be reproduced on one type of paper may be impossible to reproduce on another. Even with a properly calibrated system and a correctly configured ICC profile, a color that lies outside the printer's gamut will be replaced by the closest reproducible color.

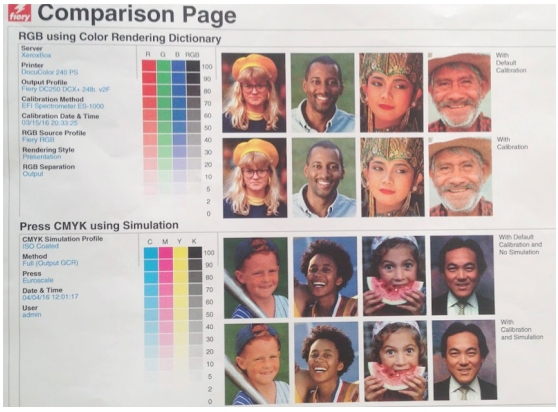
For the research, images output in various output systems were used as model images, namely: prints printed using the Heildenberg MOV offset printing method, digital machine HP Indigo press ws6800p, digital laser multifunction device Xerox DocuColor240PS and digital Konica Minolta bizhub C224.



» **Figure 1.** *Offset machine Heildenberg MOV*



» **Figure 2.** *Digital HP Indigo press ws6800p*



» **Figure 3.** *Digital Laser Multifunction Device*



» **Figure 4.** *Digital Konica Minolta bizhub C224*

To assess the color reproduction of different output systems during the study, Lab and xyY color coordinates were measured on experimental prints using Vip Spectra 2000. Measurement conditions D50, observation angle 2º, without polarizing filter, zeroing by paper color, substrate color white.

The empirical-theoretical method of studying color reproduction is based on the instrumental measurement

of print coordinates and their subsequent mathematical formalization in the form of spatial geometric models.

The advantage of the two-dimensional representation according to the CIE system is that, instead of describing color using three standard color values, X, Y, and Z, it can be represented by only two chromaticity coordinates, x and y, which characterize hue and saturation. Brightness is represented separately. The disadvantage of this representation is that it is valid only for a specific level of spectral brightness. If the spectral brightness changes, the standard color value Y must also be changed, resulting in a new diagram corresponding to that particular Y value.

To analyze the color reproduction capabilities of various printing systems and digital image preparation technologies, it is necessary to construct color gamuts on the CIE 1931 xyY chromaticity diagram. In this study, the color gamuts of the printing systems are compared with the color gamut of the Adobe RGB (1998) working color space.

3.1. Input data: xy chromaticity coordinates of experimental prints obtained from each printing system

The CIE 1931 xy chromaticity diagram was used to visualize and compare the color gamut boundaries of the evaluated printing systems against the reference Adobe RGB (1998) color space. Gamut boundaries were constructed using a 6-point chromatic vertex model comprising primary and secondary color patches (C, M, Y, R, G, B).

Spectrophotometrically measured XYZ tristimulus values for the printing systems and theoretical reference values for Adobe RGB (1998) were converted into CIE 1931 xy chromaticity coordinates using the Bruce Lindbloom Color Calculator under CIE D65 illuminant and 2º standard observer conditions, according to Eq. (1):

$$X = \frac{X}{X+Y+Z}, Y = \frac{Y}{X+Y+Z} \quad (1)$$

where X, Y, Z represent the tristimulus values, and x, y denote the calculated chromaticity coordinates.

The calculated chromaticity coordinates are summarized in Table 1. All data processing and 2D polygon constructions were carried out using Origin software (OriginLab Corp.).

Superimposing the reference Adobe RGB (1998) gamut onto the printed systems' polygons enables direct identification of color clipping, saturation limits, and hue shifts across specific color sectors during the printing process. Although the CIE xy space is perceptually non-uniform—particularly due to the visually extended green region—it provides a standardized, robust, and sufficient basis for the comparative evaluation of the investigated printing technologies.

Adobe RGB (1998) is used as the working space because it is the most commonly used monitor working space in Intel-based desktop publishing systems. Adobe RGB (1998) is a radical option for prepress. Its color coverage area almost completely includes the entire CMYK color range- pure cyan corresponds to approximately 98 percent cyan, 2 percent magenta and yellow, and the gamma of Table provides visual uniformity (Table 1).

Table 1

Adobe RGB (1998) has the following chromaticity coordinates

	X	Y
Red	0.6400	0.3300
Green	0.2100	0.7100
Blue	0.1500	0.0600
White	0.3127	0.3290

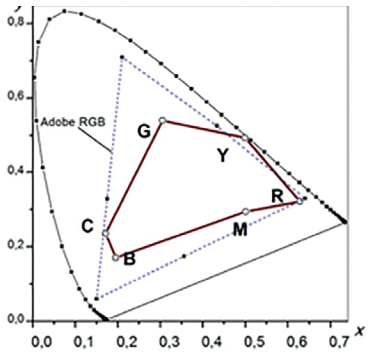
The calculated chromaticity coordinates for the 7 primary and secondary color vertices (C, M, Y, R, G, B) are summarized in Tables 2-5. All coordinate data were imported into Origin software (OriginLab Corp.) to generate 2D chromaticity polygons and perform comparative visual.

Table 2

Digital printing on the machine Konika Minolia Bizhub C 224

	X	Y
Cyan	0,171	0,235
Blue	0,195	0,171
Magenta	0,501	0,295
Red	0,628	0,322
Yellow	0,499	0,493
Green	0,305	0,54

We construct color coverings based on color coordinates.

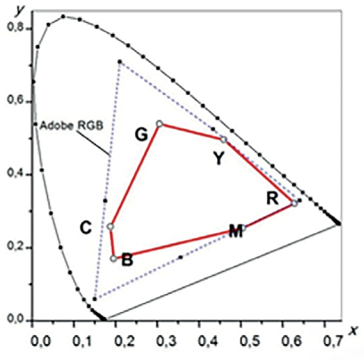


» **Figure 5:** *Color gamut on the machine Konika Minolia Bizhub c224*

Table 3

HP Indigo press ws6800p

	X	Y
Cyan	0,187	0,258
Blue	0,195	0,171
Magenta	0,504	0,254
Red	0,628	0,322
Yellow	0,459	0,497
Green	0,305	0,54
Green	0,305	0,54

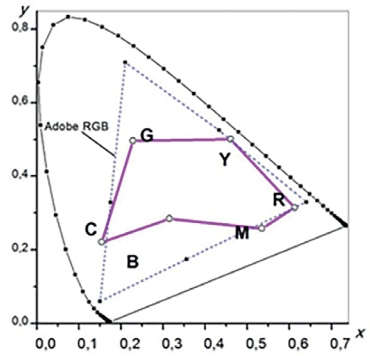


» **Figure 6:** *Color gamut HP Indigo press ws6800p*

Table 4

Laser digital multifunction copier DocuColor240PS

	X	Y
Cyan	0,154	0,221
Blue	0,315	0,285
Magenta	0,535	0,258
Red	0,612	0,315
Yellow	0,461	0,501
Green	0,228	0,497

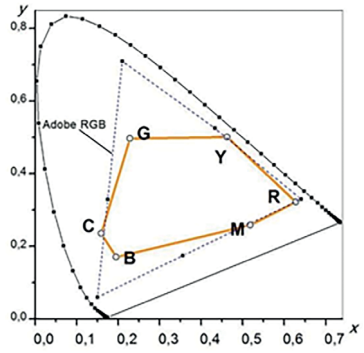


» **Figure 7:** *Color gamut of laser digital multifunction device DocuColor240PS*

Table 5

Offset press Heildenberg MOV

	X	Y
Cyan	0,154	0,221
Blue	0,315	0,285
Magenta	0,535	0,258
Red	0,612	0,315
Yellow	0,461	0,501
Green	0,228	0,497



» **Figure 8:** *Color gamut an offset press Heildenberg MOV*

Based on the constructed color gamuts, the digital printing machine HP Indigo Press WS6800P demonstrated the widest color coverage and the closest approximation to the reference color gamut.

3.2. Production time of products by different output systems

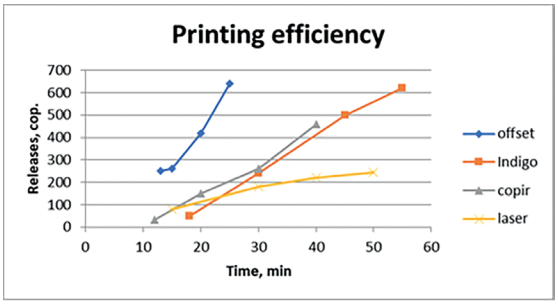
The speed of production is the main advantage of digital machines. There are cases when the customer is ready to pay twice the price for urgent production of products. It is known that color copies are not expensive. It is clear that the preparation and printing time on a printing machine is longer than on a digital one.

For further analysis, the next stage involved preparing data obtained from various output devices. The actual production time was determined and is presented in minutes for different print run volumes (Table 6).

Table 6
Time to print a contribution on different output systems

	Time, min	Realeses, cop.
Offset	13	250
	15	260
	20	420
	25	640
Indigo	18	50
	30	240
	45	500
	55	620
Copir	12	34
	20	150
	30	260
	40	460
Laser	15	80
	30	180
	40	220
	50	245

Based on production data (Table 6),
a dependence was built



» **Figure 9:** *Efficiency of product manufacturing on various equipment*

The dependence shown in Fig. 9 illustrates the number of prints that can be produced on different types of equipment over a specified period of time. For print runs of up to 300 copies, the highest productivity is achieved by the Konica Minolta Bizhub C224 and the Xerox DocuColor 240 multifunctional printing system, whereas large print runs are most efficiently produced using offset printing equipment. The simple linear nature of the dependence is explained by the fact that only two characteristics of each printing device were used for its construction: the time required for preparatory operations and the maximum production speed.

4. Discussion

The geometric reconstruction of the 3D color gamuts in the CIELAB space confirmed that the digital liquid toner technology utilized in the HP Indigo system achieves a more comprehensive and stable color volume compared to conventional offset lithography. This phenomenon can be scientifically interpreted through the lens of print macrostructure and ink-substrate chemistry.

Conventional offset printing is inherently bound by the mechanics of ink film splitting and a relatively thick ink layer (often leading to a higher variance in dot gain), which can restrict the boundary saturation of chromatic primaries, particularly on standard substrates, as observed by Blahová et al. (2025). On the contrary, the liquid electrophotographic toner (ElectroInk) forms an extremely thin, uniform polymeric film that completely transfers to the substrate without absorbing deep into the fibers. This minimizes optical dot gain and preserves the chromatic purity of the primary (CMY) and secondary (RGB) clusters.

Our findings closely align with the benchmarking criteria established by Mika et al. (2025), who demonstrated that digital liquid toners provide superior color accuracy in high-saturated blue and magenta zones. When mapped using the modern human visual system simulations advocated by (Urban et al., 2023), the expanded volume of the Indigo's gamut represents not just a mathematical abstraction, but a noticeable improvement in visual fidelity, making it highly suitable for high-fidelity Expanded Color Gamut (ECG) applications (Malik et al., 2024).

The interpretation of the temporal data provides a clear techno-economic demarcation between digital and conventional systems. The generated operational efficiency curves illustrate a classic trade-off between setup time and run speed.

For low-volume production (small print runs), the digital platform demonstrates overwhelming operational dominance. This is directly attributed to the complete elimination of prepress workflows, such as computer-to-plate (CTP) manufacturing, plate mounting, and physical press ink-key calibration. As digital press workflows feed data directly to the imaging cylinder, the "time-to-market" for the first print is virtually instantaneous. This operational flexibility supports the contemporary shift toward short-run, localized print demands documented by Keypoint Intelligence and Senkivskyy et al. (2023).

However, as the run length increases, a definitive crossover point is reached. The high mechanical speed of modern offset presses rapidly dilutes the fixed initial time investment required for prepress preparation. Once the press is calibrated and running, the marginal

time per individual print in offset lithography drops significantly below that of high-volume digital systems.

This dynamic is perfectly synchronized with the hybrid production models evaluated by Rovira et al. (2024), confirming that the operational curves are governed by predictable time-efficiency laws. The choice of equipment cannot be based solely on colorimetric capacity; it must balance the volumetric color space requirement against the volume of the print run to optimize both quality and time-efficiency.

5. Conclusions

The study employed an empirical-theoretical method for investigating color reproduction, based on the instrumental measurement of print color coordinates and their subsequent mathematical formalization in the form of spatial geometric models. The research was carried out using prints produced by various output systems. Based on the measured color coordinates, color gamuts of multicolor prints were constructed on the CIE chromaticity diagram.

Analysis of the constructed color gamuts showed that the HP Indigo Press WS6800P digital printing machine provides the widest color coverage, indicating superior color reproduction capabilities compared to the other investigated systems.

It was also demonstrated that digital printing machines are optimal for small print runs due to their high production speed and operational efficiency. In contrast, offset printing machines are more suitable for large print runs, where reducing the unit cost of production becomes a decisive factor.

Therefore, when selecting a printing technology, it is important to consider both the print run volume and the required production time. Digital printing is advantageous for urgent and small-volume orders, whereas offset printing is more efficient for large-volume production.

6. Acknowledgments

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