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# Comprehensive Review of Technical and Material Factors Influencing Offset Print Quality

Spomenko Kešina
Irma Horvat
Dean Valdec
Petar Miljković

University North,
Varaždin, Croatia

**ABSTRACT**

*Offset print quality emerges from coupled interactions among standardized process control, substrate structure and surface chemistry, ink formulation and rheology, and post-print finishing. Although these factors are frequently investigated separately, their combined influence on ink transfer, film formation, tone value increase, gloss, colour stability, and final visual appearance remains insufficiently synthesized. This critical review evaluates the technical and material factors governing offset print quality through an integrated process-material perspective. It examines the role of ISO 12647-2-based process control and objective measurement, then compares evidence concerning paper grammage, roughness, porosity, coating composition, surface wettability, ink formulation, ink sequence, varnishing, and drying or curing methods. Particular attention is given to the mechanisms that connect substrate properties and ink behaviour, including wetting, capillary penetration, pigment retention, ink setting, film levelling, and optical changes caused by transparent finishing layers. The review shows that individual indicators such as grammage, roughness, or water contact angle cannot independently predict printability because their effects depend on coating structure, surface-energy components, ink-vehicle polarity, dampening conditions, and ink rheology. It further identifies limitations in the current literature, including inconsistent characterization methods, insufficient separation of aqueous and non-aqueous wetting behaviour, and limited integration of sustainability and end-of-life criteria. The review concludes that high quality and sustainable offset printing requires both standards based measurement and a mechanism oriented understanding of material–process interactions.*

**KEY WORDS**
Critical review, ink formulation, ISO 12647-2, offset printing, paper properties, print quality, surface coatings, surface wettability

## 1. Introduction

Achieving consistent and high quality results in offset printing is a persistent challenge because print quality emerges from the interaction of press conditions, colour management procedures, substrates, inks, fountain solution, and finishing processes (Özakhun, Zelzele & Özcan, 2012). Parameters such as colour difference, solid ink density, tone value increase, trapping, gloss, print contrast, and grey balance are therefore not independent quality attributes. Instead, they are observable outcomes of coupled material-process interactions.

ISO 12647-2 provides an important basis for controlling offset lithographic production through defined targets, tolerances, substrates, screening conditions, and measurement procedures. However, standards-based control alone does not explain why identical nominal settings can produce different results on different paper grades, coating structures, ink systems, or finishing combinations. For this reason, reliable process control must be sup-

ported by an understanding of the physical and chemical mechanisms governing ink transfer, ink setting, pigment retention, film levelling, and optical light scattering.

Despite the extensive body of research on individual aspects of offset printability, the literature remains fragmented across process standardization, substrate engineering, ink formulation, and post print finishing. Studies often report changes in optical density, tone value increase, gloss, or colour difference under specific experimental conditions, but the mechanisms connecting these outcomes are not always evaluated consistently. In particular, the effects of surface topography, pore structure, surface free energy, ink rheology, setting behaviour, and transparent finishing layers are frequently treated as separate variables, although they jointly govern ink transfer, film formation, light scattering, and final colour appearance.

Therefore, this review critically examines the technical and material factors governing offset print quality through an integrated process-material framework. Rather than only compiling reported results, the review compares the conditions under which findings converge or diverge, identifies the physical mechanisms proposed to explain these effects, and highlights limitations in the current evidence. The review focuses on four interdependent domains: (i) standards-based process control and colour measurement, (ii) paper and coating properties, (iii) ink formulation, rheology, and ink sequence, and (iv) varnishing, coating, and drying processes.

The objectives are to: (1) identify the dominant material and process variables affecting colour reproduction, tone value increase, gloss, and print uniformity; (2) explain the mechanisms through which those variables interact; (3) evaluate where findings are substrate or process specific and cannot be generalized directly; and (4) define research gaps relevant to sustainable, high fidelity offset printing. By linking standards based control with material-process interactions, the review aims to provide a more coherent basis for future experimental work and industrial process optimization.

The literature was identified through searches of scholarly databases and publisher platforms using combinations of the terms “offset printing,” “print quality,” “ink transfer,” “paper coating,” “surface energy,” “tone value increase,” “colour management,” “varnishing,” and “UV curing.” Priority was given to peer-reviewed publications, international standards, and recent studies addressing mechanisms or measurement based evaluation. Earlier foundational studies were retained where they introduced methods or concepts still used in contemporary research. The review is narrative and critical rather than meta-analytical; consequently, differences in experimental design, substrate class, ink system, measurement geometry, and finishing conditions are explicitly considered when interpreting findings.

## 2. Quality standards and assurance in offset and digital printing

Achieving consistent and high-quality print production requires the systematic application of international standards, measurement protocols, and quality assurance frameworks. In offset lithography, ISO 12647-2 provides a central framework for process control by specifying target values, tolerances, substrates, screening conditions, proofing requirements, and measurement procedures for colour reproduction. This standard defines target values and tolerances for essential quality indicators such as CIE Lab* color values, solid ink densities, tone value increase (dot gain), print contrast, trapping, and gray balance, as well as requirements for substrates, screening, and measurement methods (International Organization for Standardization, 2013). By following these guidelines, print results are visually and metrically consistent across different runs and facilities, with Table 1 in ISO 12647-2 2013 providing CIELAB coordinates and gloss values for typical paper types as a key reference for substrate selection and process control.

**Table 1**

Print substrate specifications according to ISO 12647-2:2013 (International Organization for Standardization, 2013)

| Characteristics | Paper type and surface | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PS1 | | | PS2 | | | PS3 | | | PS4 | | |
| Type of surface | Premium coated | | | Improved coated | | | Standard glossy coated | | | Standard matte coated | | |
| Mass-per-area[a] g/m² | 80 to 250 (115) | | | 51 to 80 (70) | | | 48 to 70 (51) | | | 51 to 65 (54) | | |
| CIE Whiteness[b] | 105 to 135 | | | 90 to 105 | | | 60 to 90 | | | 75 to 90 | | |
| Gloss[c] | 10 to 80 | | | 25 to 65 | | | 60 to 80 | | | 7 to 35 | | |
| Colour[d] | Coordinates | | | Coordinates | | | Coordinates | | | Coordinates | | |
| | L* | a* | b* | L* | a* | b* | L* | a* | b* | L* | a* | b* |
| White backing | 95 | 1 | -4 | 93 | 0 | -1 | 90 | 0 | 1 | 91 | 0 | 1 |
| Black backing | 93 | 1 | -5 | 90 | 0 | -2 | 87 | 0 | 0 | 88 | 0 | -1 |
| Tolerance | ±3 | ±2 | ±4 | ±3 | ±2 | ±2 | ±3 | ±2 | ±2 | ±3 | ±2 | ±2 |
| Fluorescence[e] | moderate | | | low | | | low | | | low | | |

| Characteristics | Paper type and surface | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PS5 | | | PS6 | | | PS7 | | | PS8 | | |
| Type of surface | Premium coated | | | Improved coated | | | Standard glossy coated | | | Standard matte coated | | |
| Mass-per-area[a] g/m² | 70 to 250 (120) | | | 38 to 60 (56) | | | 40 to 56 (49) | | | 40 to 52 (45) | | |
| CIE Whiteness[b] | 140 to 175 | | | 45 to 85 | | | 40 to 80 | | | 35 to 60 | | |
| Gloss[c] | 5 to 15 | | | 30 to 55 | | | 10 to 35 | | | 5 to 10 | | |
| Colour[d] | Coordinates | | | Coordinates | | | Coordinates | | | Coordinates | | |
| | L* | a* | b* | L* | a* | b* | L* | a* | b* | L* | a* | b* |
| White backing | 95 | 1 | -4 | 90 | 0 | 3 | 89 | 0 | 3 | 85 | 1 | 5 |
| Black backing | 92 | 1 | -5 | 87 | 0 | 2 | 86 | -1 | 2 | 82 | 0 | 3 |
| Tolerance | ±3 | ±2 | ±2 | ±3 | ±2 | ±2 | ±3 | ±2 | ±2 | ±3 | ±2 | ±2 |
| Fluorescence[e] | high | | | low | | | faint | | | faint | | |

Visual inspection remains useful for identifying gross defects, but it is insufficient as the sole basis for process control because visual judgement is influenced by illumination, observer adaptation, viewing geometry, and the absence of numerical tolerances. Objective measurement of CIE L*a*b* values, solid ink densi-

ty, tone value increase, trapping, grey balance, and print contrast enables deviations to be quantified and corrected systematically. The study conducted in an Egyptian printing house demonstrated that an offline quality control procedure based on ISO 12647-2 improved conformance without replacing existing equipment or materials (Mostafa, 2016).

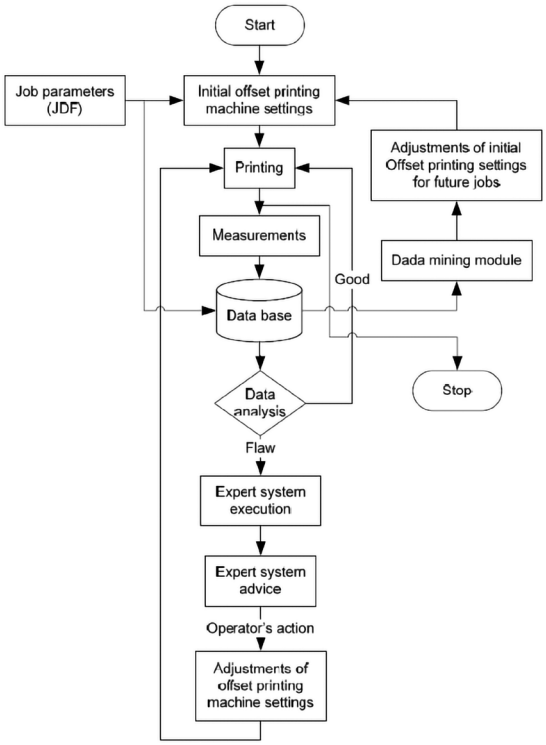
The reported improvement should be interpreted in relation to the specific press, substrate, RIP configuration, operator practice, and measurement protocol used in that study. It demonstrates the value of measurement based feedback, but it should not be generalized as a universal performance gain for all offset printing environments. More broadly, the evidence indicates that the greatest benefit of ISO based control arises when prepress linearization, characterization, press calibration, and production verification are treated as a continuous feedback loop rather than as isolated quality checks (Mostafa, 2016).

**Table 2**

Tone value inputs for RIP calibration and adjustment of reproduction curves to minimize tone value increase (Mostafa, 2016)

| Dot % | Target Black % | Target Cyan % | Target Magenta % | Target Yellow % |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 2 | 1.5 | 1.5 | 1.5 | 1.5 |
| 5 | 3.8 | 3.5 | 3.8 | 3.5 |
| 10 | 7.5 | 7.7 | 7.7 | 7 |
| 20 | 14.7 | 14.5 | 14.7 | 14.2 |
| 25 | 18.3 | 18.2 | 18.7 | 18 |
| 30 | 22 | 22 | 22.8 | 22 |
| 40 | 29.5 | 30.5 | 32 | 30.5 |
| 50 | 37.5 | 40.8 | 42.5 | 40.3 |
| 60 | 46 | 50 | 53.2 | 50.5 |
| 70 | 55.2 | 60 | 63.8 | 60 |
| 75 | 59.8 | 65.2 | 68.8 | 64.5 |
| 80 | 64.5 | 70.8 | 74 | 69 |
| 90 | 75.5 | 82.8 | 86.5 | 79 |
| 95 | 82.9 | 91 | 93.5 | 86.3 |
| 100 | 0 | 0 | 0 | 0 |

Quality assurance frameworks can extend measurement based control by storing job parameters, press settings, measurement results, and corrective actions in a traceable database (Korytkowski, Olejnik-Krugły & Zaikin, 2009). Such systems allow deviations to be linked to recurring combinations of substrate, ink, press settings, and production conditions. In the framework (Figure 1) proposed by Korytkowski, Olejnik-Krugły and Zaikin (2009), measured data is analysed to identify a quality flaw, after which an expert system proposes corrective action and the resulting outcome is fed back into the database. The scientific value of this approach lies not only in automation, but in its potential to reveal causal patterns that are difficult to identify through isolated measurements. However, expert system recommendations are only as reliable as the quality, completeness, and representativeness of the recorded data. A system trained on one press, paper family, or ink set may not transfer directly to another production environment. Future work should therefore validate data-driven quality-control systems across multiple presses, substrates, and operating conditions.




» **Figure 1:** *Quality assurance framework algorithm (Korytkowski, Olejnik-Krugły & Zaikin, 2009)*

As demonstrated in a Croatian study, systematically measuring essential parameters, including density, dot gain, gray balance, and trapping with standardized control strips and devices is fundamental to optimizing and standardizing print reproduction. Through iterative adjustment of RIP curves and press settings, deviations from ISO targets are minimized (Valdec, Ivančić & Vusić, 2009). Emphasis is placed on starting quality control in prepress, not just during print production, resulting in a reproducible, high-quality process that aligns with international standards regardless of operator or machine variability. Taken together, the reviewed studies support a common conclusion: quality control should begin before production and continue throughout the printing workflow. Calibration curves and press adjustments are not universally transferable because they are influenced by the interaction of the RIP, screening method, plate,

ink set, fountain solution, press condition, substrate, and measurement instrument. Thus, standardization does not eliminate material variability; rather, it provides a controlled framework within which material specific behaviour can be measured, documented, and compensated (International Organization for Standardization, 2013; Korytkowski, Olejnik-Krugły & Zaikin, 2009; Mostafa, 2016; Valdec, Ivančić & Vusić, 2009 ).

## 3. Paper and surface effects on offset print quality

Paper affects offset print quality through a combination of bulk structure, surface topography, coating chemistry, pore geometry, compressibility, and liquid-uptake behaviour. Consequently, properties such as grammage, thickness, density, air permeability, and roughness should not be interpreted as independent causes of print-quality changes. In practical paper grades, these parameters are often correlated with one another and with unmeasured variables such as coating weight, pore-size distribution, binder distribution, and calendering intensity.

Tutuş, Yılmaz and Çiçekler (2017) reported that increasing grammage, thickness, and air permeability was associated with higher tone value increase, print contrast, and trapping, while print density could decrease. These outcomes should not be interpreted as evidence that grammage or thickness alone determines printability. A more open and compressible substrate structure can alter pressure distribution and ink-vehicle penetration, while the surface can retain or lose pigment differently depending on coating coverage and porosity. Thus, the relationships observed in the study are best understood as combined structural effects of the tested paper grades rather than universal causal effects of individual physical parameters (Havlínová et al., 2000; Sonmez et al., 2022).

Table 3 presents the measured grammage, thickness, and roughness values for the paper grades evaluated by Tutuş, Yılmaz and Çiçekler (2017); it also demonstrates that the compared papers differ in several physical characteristics simultaneously.

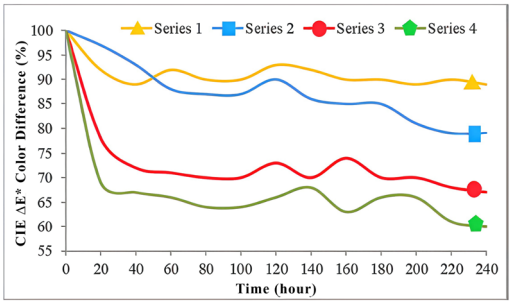
Surface roughness is an important but incomplete indicator of substrate suitability for offset printing. Smoother surfaces can improve the uniformity of ink transfer, promote more continuous ink film formation, and reduce diffuse scattering, thereby increasing apparent gloss and optical density. However, roughness measurements alone do not describe pore geometry, coating heterogeneity, or the chemical affinity between the ink vehicle and the substrate. These additional factors can determine whether ink remains near the surface, penetrates into the coating, or forms a non-uniform film.

**Table 3**

Physical properties of each tested paper (Tutuş, Yılmaz & Çiçekler, 2017)

| Physical properties | Grammage ($g/m^2$) | Thickness (Micron) | Roughness (ml/min) |
|---|---|---|---|
| American Bristol 230gsm | 224 | 300 | 2.4 |
| American Bristol 350gsm | 342 | 475 | 170 |
| Coated Matt | 115 | 90 | 0-3 |
| Coated Gloss | 115 | 110 | 5 |
| I. High Grade 70gsm | 70 | 85 | 302 |
| I. High Grade 80gsm | 78 | 100 | 366 |
| II. Med Grade 48gsm | 49 | 75 | 75 |
| II. Med Grade 54gsm | 54 | 83 | 104 |
| III. Low Grade 70gsm | 71 | 120 | 103 |
| III. Low Grade 80gsm | 81 | 85 | 339 |

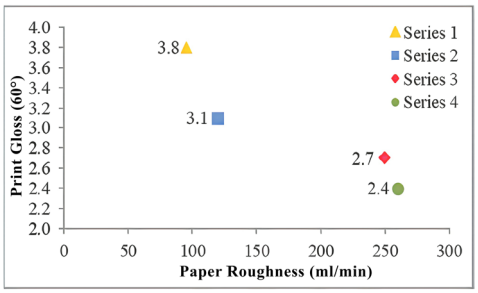
Aydemir et al. (2021) reported that the smoother uncoated papers examined in their study had lower water contact angles, higher measured surface energies, higher print gloss, and better colour stability. The finding is consistent with improved surface uniformity and aqueous wettability, but it should be interpreted carefully. Because the contact angle was measured using water, it primarily characterizes interaction with an aqueous liquid, not necessarily with the predominantly hydrophobic vehicle of conventional offset inks. The relationship between water wettability and offset ink setting therefore depends on the polar and dispersive components of surface energy, coating or fibre chemistry, pore structure, fountain-solution behaviour, and ink formulation (Hubbe, Gardner & Shen, 2015; Özakhun, Zelzele & Özcan, 2012). Figure 2 shows the time dependent colour difference behaviour of the tested paper samples and indicates that the observed colour stability was associated with their measured surface characteristics.




» **Figure 2:** *Impact of surface characteristics on ink color change (Aydemir et al., 2021)*

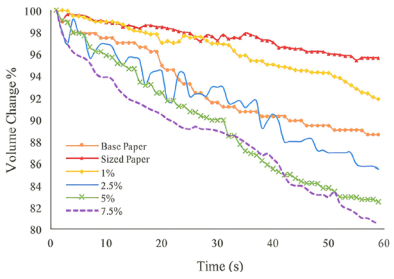
The combined evidence nevertheless suggests that a uniform, smooth, and well controlled substrate surface

is generally advantageous for gloss and colour stability (Aydemir et al., 2021). Future studies should pair roughness data with measurements of coating porosity, surface energy components, liquid penetration kinetics, and direct ink setting behaviour so that the mechanisms behind observed print quality differences can be separated more reliably. Figure 3 visualizes the association between paper roughness and print gloss for the investigated samples, supporting the view that a smoother surface can facilitate a more uniform reflective ink film.




» **Figure 3:** *Relationship between paper roughness and print gloss (Aydemir et al., 2021)*

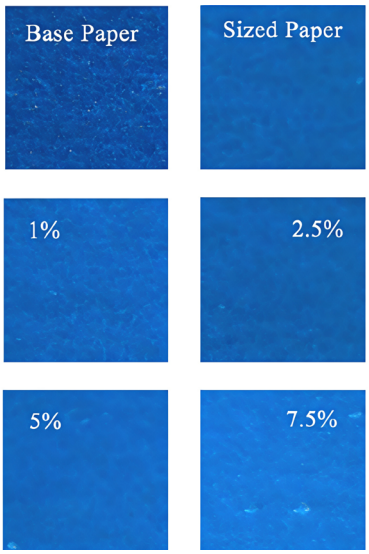
Surface coatings containing calcium carbonate ($CaCO_3$) pigment and cationic starch are used to tailor coating porosity, smoothness, liquid uptake, gloss, and printability (Kandirmaz et al., 2020). Their effect cannot be reduced to a single "absorbency" variable, because the coating controls both the chemical affinity of the surface and the capillary structure through which liquids penetrate. In the study of Kandirmaz et al. (2020), surface sizing increased the measured surface energy and reduced the water contact angle, indicating enhanced wettability toward water. This result should be interpreted primarily in relation to aqueous liquids and fountain solution interactions; it does not, on its own, demonstrate increased absorption of conventional oil based offset inks (Özakhun, Zelzele & Özcan, 2012). The changes in water drop volume observed for the differently treated paper surfaces are illustrated in Figure 4 and should likewise be interpreted as water related liquid uptake behaviour rather than as a direct measure of conventional offset-ink absorption.




» **Figure 4:** *Variation of water drop volume on papers with distinct surface treatments (Kandirmaz et al., 2020)*

A lower water contact angle may indicate a more hydrophilic surface, which can facilitate water uptake or interaction with the dampening solution (Aydemir et al., 2021; Kandirmaz et al., 2020). However, for solvent or oil based ink vehicles, the relevant variables include the dispersive and polar components of surface free energy and the contact angle of representative non polar liquids or the ink vehicle itself. A hydrophilic surface may not necessarily favour penetration of a hydrophobic vehicle; indeed, incompatibility can reduce wetting and retard ink setting. Therefore, conclusions about offset ink absorption should be supported by ink or oil specific contact angle measurements, liquid penetration tests, ink setting measurements, or direct printability measurements rather than water contact angle alone (Hubbe, Gardner & Shen, 2015).

In the study of Kandirmaz et al. (2020) as the $CaCO_3$ content increased, the reported surface energy decreased and the water contact angle increased. In a coating formulation, this trend may reflect changes in pigment packing, accessible binder at the surface, pore structure, and surface heterogeneity. At high pigment concentrations, inadequate dispersion or insufficient binder can promote agglomeration of $CaCO_3$ pigment particles. These agglomerates may increase roughness and create a non-uniform coating topography, potentially impairing ink-film levelling and lowering print gloss. However, the effect is formulation specific: $CaCO_3$ particle size, morphology, dispersant, latex or starch binder level, coating weight, drying conditions, and calendering all influence the final surface (Kandirmaz et al., 2020). Microscopic images of cyan solid tone prints produced on surfaces containing different $CaCO_3$ amounts are presented in Figure 5, illustrating how changes in coating formulation can be reflected in the local uniformity and visual appearance of the printed ink film.




» **Figure 5:** *Cyan solid tone print on different surfaces under 90x magnification (Kandirmaz et al., 2020)*

The practical implication is that water contact angle should not be used as a stand-alone indicator of offset printability. A rigorous evaluation should combine water and non polar liquid wetting measurements with porosity or liquid uptake tests, surface-topography characterization, ink setting assessment, optical density, gloss, tone value increase, and colour-difference measurements. Such a multi parameter approach would distinguish whether a change in print quality is driven primarily by interfacial wetting, capillary penetration, pigment retention at the surface, or ink-film levelling.

The optimum coating formulation must balance surface smoothness, porosity, chemical affinity, mechanical integrity, and ink setting behaviour. Cationic starch can contribute to surface consolidation and smoothness, but the resulting printability depends on the amount of starch, its interaction with pigments and binders, the final pore structure, and the polarity of the liquid contacting the surface (Kandirmaz et al., 2020). Therefore, neither greater hydrophobicity nor greater hydrophilicity should be considered intrinsically favourable without reference to the specific ink vehicle and fountain solution system.

Print gloss is a perceptual and optical indicator strongly influenced by the smoothness and continuity of the printed ink film. Coating composition, coating weight, solids content, pigment packing, supercalendering conditions, and internal or surface sizing can all influence gloss because they modify surface topography and the extent to which the ink film can level before setting.

Elsayad et al. (2001) reported that higher supercalendering pressure and temperature, increased coating solids, and thicker coating films enhanced print gloss. These findings are consistent with the mechanism that a smoother and more uniform coating permits more regular ink transfer and ink film leveling, reducing micro scale surface irregularities that scatter light diffusely. Conversely, high mechanical pulp content or excessive internal sizing can increase roughness or modify liquid uptake, thereby reducing gloss. The reported benefit of plastic pigment in calcium carbonate based coatings further illustrates that gloss depends not simply on pigment chemistry, but on the packing, deformability, and surface forming behaviour of the complete coating formulation (Kandirmaz et al., 2020; Sonmez et al., 2022).

# 4. Ink formulation, sequence, and interaction with substrates in offset printing

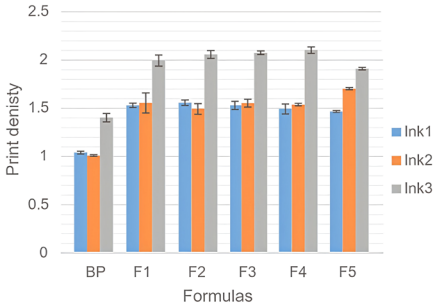
Ink formulation and substrate properties must be considered as an interacting system rather than as separate determinants of offset print quality. During printing, the ink splits between rollers, plate, blanket, and substrate. The ink vehicle may penetrate the coating or paper structure while pigment and binder components remain at or near the surface. The balance between transfer, setting, penetration, and film levelling is influenced by ink viscosity, tack, thixotropy, pigment concentration, vehicle polarity, substrate roughness, porosity, coating chemistry, and press conditions.

Studies of kaolin and precipitated calcium carbonate (PCC) coatings show that a greater proportion of kaolin can improve surface smoothness, print gloss, and print density (Sonmez et al., 2022). However, the outcome should not be attributed to pigment identity alone. Kaolin and PCC differ in morphology, packing behaviour, pore structure, and interactions with the latex binder. These characteristics influence the distribution of the ink vehicle and the extent to which pigment remains close to the surface, both of which affect optical density and gloss (Sonmez et al., 2022). Table 4 presents the kaolin-PCC formulation gradient used in the cited study, with latex content held constant, and therefore provides the material basis for comparing the resulting print density and gloss behaviour.

**Table 4**
Coating formulations of coated cardboard samples (Sonmez et al., 2022)

| Coatings | F1 | F2 | F3 | F4 | F5 |
|---|---|---|---|---|---|
| **Kaolin** | - | 30 | 50 | 70 | 100 |
| **PCC** | 100 | 70 | 50 | 30 | - |
| **Latex** | 10 | 10 | 10 | 10 | 10 |

The finding that UV inks produced the highest density and gloss in the reviewed coating study is also mechanistically plausible because rapid curing can preserve a continuous, high solids ink film at the surface (Sonmez et al., 2022). Nevertheless, comparisons between UV, mineral oil based, and vegetable oil based inks must account for differences in curing mechanism, ink film thickness, substrate compatibility, colourant formulation, and measurement time. Plant derived inks may offer environmental advantages, but their performance should be evaluated using the full set of relevant criteria: colour reproduction, gloss, rub resistance, drying or curing energy, VOC emissions, migration requirements where applicable, deinkability, and recyclability. Figure 6 compares the print density measurements obtained for the different coating formulations and ink systems, showing that the observed optical response reflects the combined effects of pigment composition and ink type rather than a single coating variable.

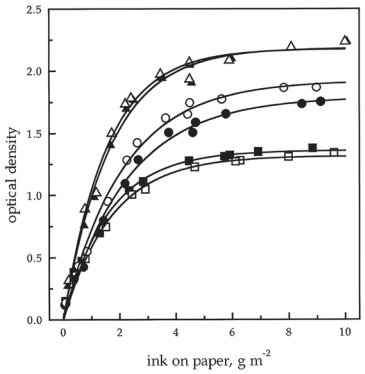



» **Figure 6:** *Print density measurements of coated cardboard samples with various formulations (Sonmez et al., 2022)*

Offset inks are viscoelastic, pseudoplastic, and thixotropic materials, and these rheological properties influence both transfer and film formation (Havlínová et al., 2000; Jasurek et al., 2018). High enough tack is needed for stable transfer through the inking train, but excessive tack can increase picking risk or undesirable ink splitting on weak or porous substrates (Jasurek et al., 2018). Viscosity and thixotropy determine how the ink responds under the high shear conditions of printing and how it levels after transfer. Therefore, a reported print-density or gloss difference cannot be attributed to substrate properties alone when ink rheology differs.

The ink mileage models applied by Havlínová et al. (2000) showed that smoother, brighter, and less absorbent papers reached higher saturation densities with more efficient ink transfer. This result supports the view that substrates capable of retaining pigment near the surface tend to produce higher optical density. However, reduced absorbency is not universally advantageous. If ink setting is too slow, it can create problems with set off, trapping, drying, or production speed. Optimal substrate behaviour therefore requires a balance between sufficient surface retention for optical performance and sufficient vehicle uptake or curing for stable production. The substrate dependent ink mileage curves and their different saturation density plateaus are illustrated in Figure 7, based on IGT black offset-ink tests modelled using the Tollenaar-Ernst equation (Havlínová et al., 2000).

The vehicle composition of offset inks influences wetting, penetration, setting, gloss, lightfastness, cleaning behaviour, VOC emissions, and suitability for specific applications. Aydemir et al. (2018) reported that linseed soybean based ink produced the highest gloss in their experiment, whereas mineral oil based ink showed greater resistance to fading on coated paper. In the same study, soy-based ink produced lower gloss values. These findings demonstrate that oil source can affect visual performance, but they should not be generalized as universal rankings because the outcome also depends on pigment composition, resin system, drying additives, substrate coating, ink-film thickness, and measurement conditions.




» **Figure 7:** *Ink mileage curves for several paper types, calculated via the Tollenaar-Ernst equation from IGT black offset ink tests. The symbols denote specific sides of each substrate: OC (■ top, □ bottom), SP (● top, ○ bottom), and SA 2:M (▲ top, △ bottom) (Havlínová et al., 2000)*

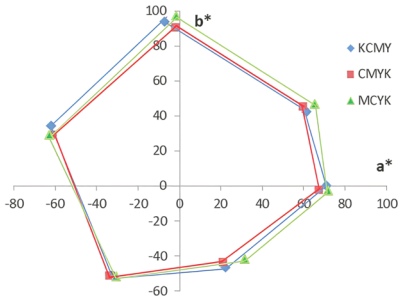
Vegetable oil based inks can reduce dependence on petroleum derived vehicles and may offer lower VOC emissions or easier cleaning in certain formulations (Aydemir et al., 2018). However, “bio based” does not automatically mean superior environmental performance or universal suitability for food packaging. A robust comparison should consider the complete formulation, drying mechanism, migration behaviour where relevant, emissions, energy use, recyclability, deinkability, and end-of-life effects alongside print quality metrics.

Ink sequence can influence colour gamut, density, contrast, and trapping because each subsequently printed ink interacts with an underlying ink film whose tack, setting state, and surface condition are changing during the press run. The magnitude of this effect depends on whether printing occurs under predominantly wet-on-wet or wet-on-dry conditions, as well as on the tack sequence of the ink set, ink film thickness, substrate absorption, and press speed (Nguye, 2024; Solanki, Jangra & Garg, 2016).

On Maplitho paper, YMCK and MYCK sequences produced higher red and orange density values than CMYK and KCMY in the reviewed experiment (Solanki, Jangra & Garg, 2016). However, the effect was smaller for green and brown. This pattern suggests that ink order does not affect all overprint colours equally; its influence is strongest where the relevant colour is sensitive to trapping efficiency and the optical contribution of the underlying ink layers.

The comparison between coated and uncoated papers further illustrates the importance of substrate dependent setting behaviour. On coated paper, MCYK sequences

produced a more extensive colour gamut, particularly in the red region, whereas uncoated paper showed smaller differences among sequences because rapid absorption reduced the duration of wet-on-wet interaction (Nguye, 2024). Thus, sequence optimization is most likely to be beneficial on less absorbent coated substrates, where ink trapping and interlayer interaction remain significant. It should not be assumed that a single preferred sequence applies to all papers, inks, or image contents. The colour gamut differences among the tested ink sequences on coated paper are illustrated in Figure 8, supporting the conclusion that sequence effects become more apparent when wet-on-wet trapping and interlayer interactions remain significant.

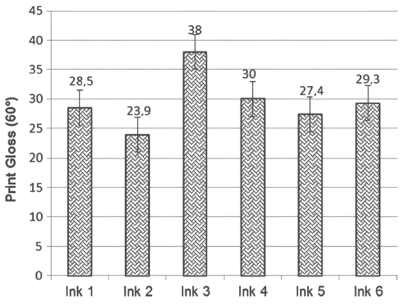



» **Figure 8:** *Color gamuts at different color sequences on coated papers (Nguye, 2024)*

Colour mixing components such as transparent and opaque white modify the rheology, optical opacity, and film forming behaviour of process inks. Transparent white can increase viscosity and tack, while also allowing greater optical contribution from the underlying substrate or ink layer. Opaque white introduces stronger light scattering and can reduce apparent chroma or gloss depending on the formulation and substrate (Aydemir et al., 2017).

In the reviewed study, mixtures containing a higher proportion of transparent white produced higher gloss and colour density than mixtures containing more opaque white (Aydemir et al., 2017). This result is consistent with improved ink film continuity and lower optical scattering, but the optimum mixture remains application specific. A formulation selected for high gloss may not be optimal for opacity, colour matching, surface uniformity, or print stability. The variation in print gloss among the tested ink mixtures on matt-coated paper is shown in Figure 9, illustrating that changes in colour mixing components can alter the optical appearance of the printed surface.

Ink consumption is a critical technical, economic, and environmental variable. Increasing ink quantity beyond the level required for target colour reproduction can prolong drying, increase set off risk, raise energy use, and increase material consumption without producing a proportional visual benefit. In the experiment reported by Aydemir, Yenidoğan and Özsoy (2020), an ink amount of 0.752 g/m² corresponded to a print density of 1.40 and the lowest reported ΔE*ab value of 3.13.




» **Figure 9:** *Print gloss values of inks on matt coated papers (Aydemir et al., 2017)*

This numerical optimum should be understood as specific to the ink, substrate, press conditions, and measurement setup used in that study. It should not be transferred directly to other printing systems. The broader conclusion is that ink-film thickness should be optimized against defined colour targets and production constraints rather than increased indiscriminately. Future research should combine ink-consumption measurements with drying kinetics, rub resistance, set-off, VOC emissions, and recyclability indicators in order to identify genuinely sustainable operating windows.

## 5. Coating, varnishing, and surface treatments

Coatings, varnishes, and laminating films can protect the printed surface and modify its gloss, abrasion resistance, barrier properties, and tactile appearance. At the same time, a transparent finishing layer changes the optical path of incident and reflected light and can therefore alter colour coordinates, tone value increase, contrast, and the visual appearance of halftone structures. The resulting effect depends on varnish chemistry, refractive index, layer thickness, coverage, curing or drying conditions, substrate gloss, ink-film topography, and viewing geometry (Hébert, Dailliez & Simonot, 2021; Hoffstadt, 2004).

Hudika, Majnarić and Cigula (2020) reported that changing UV LED varnish coverage altered the b* coordinate, especially on light samples, and affected the optical appearance of the prints. The effect was more visually pronounced with gloss varnish because specular reflection contributed more strongly to the observed appearance. However, the reported overall colour differences remained within the ISO tolerances for the tested conditions, whereas the optimum print gloss was obtained at 100% varnish surface coverage. Rather than treating varnishing as a purely protective

operation, these findings show that finishing must be included in colour management and proofing decisions whenever colour critical reproduction is required.

Clear coatings and laminating layers can produce an optical "halo effect," in which light propagation through the transparent layer changes the apparent reflectance of halftone structures. The coating can smooth sharp optical transitions at dot edges and alter internal reflection, making halftones appear darker or producing an apparent increase in tone value. The magnitude of the effect depends on the halftone geometry, dot profile, coating thickness, refractive properties of the finishing layer, and the initial roughness of the printed surface (Hébert, Dailliez & Simonot, 2021).

This mechanism explains why finishing-induced changes are not uniform across all images. Prints with sharp halftone profiles and low initial tone value increase can be more sensitive to additional optical spreading, whereas prints already affected by substantial substrate related tone value increase may show a smaller relative change (Hébert, Dailliez & Simonot, 2021). Consequently, colour critical halftone work should be evaluated after the final finishing operation rather than only before varnishing or lamination.

In packaging applications, finishing decisions must balance colour fidelity, protection, ink coverage, production efficiency, and environmental requirements. Cigula, Hudika & Donevski (2022) showed that reducing ink coverage through grey component replacement did not necessarily compromise colour reproduction on varnished cardboard. Their results also indicated that UV varnish could produce greater tone value increase and higher colour differences in some tertiary colours than water-based or conventional offset varnishes.

The difference between varnish systems is consistent with their different film forming and optical properties. UV varnishes form rapidly cured layers that can substantially alter surface reflectance and apparent dot structure, whereas water based and conventional offset varnishes may produce smaller changes under comparable conditions (Cigula, Hudika & Donevski, 2022; Galić, Ljevak & Zjakić, 2015). However, the final effect remains dependent on coating weight, coverage, substrate roughness, ink formulation, curing conditions, and the colour being evaluated.

Spot colours require particular caution because their spectral reflectance is determined by the specific pigment mixture rather than by standard CMYK overprinting. UV varnishing, other varnish systems, and thermal lamination can alter gloss, saturation, metameric behaviour, and measured colour coordinates (Galić, Ljevak & Zjakić, 2015; Galić, 2017). Therefore, a spot colour specification should define not only the ink formulation and substrate, but also the intended finishing process, measurement geometry, backing condition, and viewing conditions.

Comparative simulations by Hoffstadt (2004) indicated that film coatings can cause stronger apparent tone value increase than varnishes, particularly at low nominal dot values. In the reported results, UV varnish caused an additional tone value increase of approximately 3–6%, dispersion varnish remained below 3%, and OPP film coatings produced substantially larger values, exceeding 12% at dot areas around 20%.

Although these values are useful for illustrating the relative optical influence of finishing systems, they should not be used as fixed compensation values in other workflows. The magnitude of finishing-induced tone value increase depends on the imaging structure, ink film topography, substrate, coating thickness, measurement condition, and film or varnish formulation. Nevertheless, the evidence supports a practical requirement: finishing-related compensation should be determined experimentally for each colour critical production combination (Hébert, Dailliez & Simonot, 2021; Hoffstadt, 2004).

The mechanisms behind finishing-related colour changes are closely connected to the condition of the underlying ink and coating layers. Coating porosity and topography influence ink setting and the uniformity of the printed film; ink viscosity and surface tension influence film levelling; and a transparent finish changes the way light interacts with the resulting microstructure. Non uniform coatings can create uneven ink setting and mottling, while an irregular ink film can produce spatial variations in gloss and colour. For this reason, finishing quality cannot be fully controlled at the finishing stage alone. It begins with the compatibility of the substrate, ink, press conditions, and pre-finish print surface (Hébert, Dailliez & Simonot, 2021; Sonmez et al., 2022).

Drying conditions during surface sizing and coating can alter the final substrate structure and thereby influence subsequent print behaviour. Yenidoğan et al. (2019) reported that oven drying produced more pronounced colour changes and lower gloss than air drying in their tested materials, whereas air drying increased surface wettability and print gloss. These results may be related to drying induced changes in binder migration, pore structure, surface chemistry, or coating stress, but the available evidence does not establish a universal ranking of drying methods.

The most appropriate drying method therefore depends on the required balance between liquid resistance, coating integrity, surface smoothness, ink setting, and final optical appearance. Because increased water wettability does not necessarily mean improved wetting by hydrophobic offset-ink vehicles, future drying studies

should distinguish water-related behaviour from ink vehicle penetration and should evaluate the complete printing system rather than the paper surface alone Hubbe, Gardner & Shen, 2015; Yenidoğan et al., 2019).

UV-curable inks and lacquers offer rapid curing, high surface gloss, and potential reductions in conventional solvent emissions (Oguz, Ozcan & Oktav, 2012). However, their performance and environmental value depend on formulation, photoinitiator chemistry, curing dose, substrate compatibility, residual-monomer or migration requirements where relevant, deinkability, and energy use. The rapid formation of a cured surface film can be advantageous for productivity and gloss, but it can also increase sensitivity to layer thickness and optical effects in colour-critical work (Hébert, Dailliez & Simonot, 2021; Oguz, Ozcan & Oktav, 2012).

Coatings and varnishes should be treated as active components of the print system rather than as post print additions. Their selection must be based on measured effects on colour, gloss, tone value increase, mechanical protection, substrate compatibility, production efficiency, and end-of-life requirements.

## 6. Research gaps and future directions

Although the reviewed literature confirms the importance of substrate, ink, and finishing variables, several limitations restrict direct comparison and generalization across studies.

Many investigations isolate one variable, such as roughness, coating pigment, or ink-oil type, while the practical offset process involves strongly coupled interactions among substrate porosity, surface chemistry, dampening conditions, ink rheology, printing pressure, and drying or curing. Future research should employ multifactorial experimental designs and report process variables in sufficient detail to support comparison (Aydemir et al., 2021).

Water contact angle is frequently used as a proxy for printability. Although it is useful for characterizing aqueous wettability, it is not sufficient to predict the setting or penetration of hydrophobic offset-ink vehicles. Future work should distinguish aqueous and non-aqueous interfacial behaviour through component-resolved surface-free-energy analysis, contact-angle measurements with liquids of different polarity, and direct ink-setting or penetration measurements (Aydemir et al., 2021).

The relationship between coating structure and visual appearance requires more standardized characterization. Surface roughness values alone cannot capture pore geometry, coating heterogeneity, pigment packing, or binder distribution (Elsayad et al., 2001; Kandirmaz et al., 2020; Sonmez et al., 2022). Combining profilometry or atomic-force microscopy with porosimetry, optical microscopy, and spectrophotometric print evaluation would provide a more complete explanation of mottle, gloss, density, and tone value increase.

Sustainable ink and coating systems require evaluation beyond their immediate optical performance. Vegetable-oil-based inks, water-based and UV/LED-curable varnishes, low-migration formulations, and recyclable or deinkable coating systems should be assessed simultaneously for colour stability, mechanical resistance, migration safety where relevant, VOC emissions, energy demand, recyclability, and compatibility with substrate recovery processes (Aydemir et al., 2018).

Digitalization of print quality control creates opportunities for more predictive process control. The combination of inline spectral measurement, job data archiving, colour management data, and machine learning models could enable early detection of deviations in ink density, tone value increase, trapping, or colour difference. However, such systems require transparent validation across press types, substrates, and environmental conditions before their industrial adoption can be generalized.

## 7. Conclusion

Offset print quality is not determined by any isolated material or process parameter. It emerges from coupled interactions between standardized process control, substrate topography and pore structure, surface chemistry, ink rheology and setting behaviour, ink sequence, and post-print finishing. ISO 12647-2 remains a central framework for reproducible colour control, but conformance requires measurement based calibration combined with a material specific understanding of the print system (International Organization for Standardization 2013; Korytkowski, Olejnik-Krugły & Zaikin, 2009; Mostafa 2016).

The available evidence supports the general advantages of smooth, well controlled coating surfaces for ink transfer, pigment retention, gloss, and colour stability (Aydemir et al., 2021; Havlínová et al., 2000; Sonmez et al., 2022). However, common indicators such as grammage, air permeability, roughness, or water contact angle should not be interpreted independently. Their relationship with print quality depends on pore structure, coating formulation, surface energy components, fountain solution interactions, ink vehicle polarity, and ink film formation (Kandirmaz et al., 2020; Tutuş, Yılmaz & Çiçekler, 2017). In particular, low water contact angle indicates improved aqueous wettability, but does not automatically

predict favourable setting or absorption of hydrophobic offset inks (Aydemir et al., 2021; Kandirmaz et al., 2020).

Ink formulation and ink sequence can influence density, gloss, trapping, and achievable colour gamut, but their effects are conditional on the substrate and press environment (Aydemir et al., 2018; Nguye, 2024; Solanki, Jangra & Garg, 2016). Similarly, varnishes, laminations, and UV-curable systems must be recognized as optical as well as protective layers because they can alter colour coordinates, tone value increase, and halftone appearance (Cigula, Hudika & Donevski, 2022; Hébert, Dailliez & Simonot, 2021; Hudika, Majnarić & Cigula, 2020). Therefore, colour critical quality assessment should be performed on the final, finished print whenever finishing is part of the intended product.

The review further indicates that environmentally preferable printing materials cannot be assessed only by immediate density or gloss (Aydemir et al., 2018; Cigula, Hudika & Donevski, 2022; Oguz, Ozcan & Oktav, 2012). Future research and industrial evaluation should integrate optical performance, mechanical resistance, drying or curing energy, VOC emissions, migration safety where relevant, recyclability, deinkability, and end-of-life effects. More recent, mechanism oriented, and statistically robust studies are needed to connect laboratory surface characterization with full-scale press performance. A future research agenda should therefore prioritize standardized multi-parameter methods, multifactorial experiments, and validated data-driven quality-control systems capable of predicting print performance across substrate and ink classes.

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