

# Impact of Substrate Surface Characteristics on Inkjet Printhead Output and Solid Ink Density Optimization of CMYK Process Colours

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## ABSTRACT

In recent years, inkjet printing has gained significant attention due to its high printing speed, economical production cost, and ability to print on a wide variety of substrates. Unlike conventional printing methods, which are showing limited growth in terms of print volume and job diversity, digital printing technologies, particularly inkjet are rapidly expanding and being widely adopted. This trend is especially noticeable in publication and packaging printing applications, where flexibility and faster turnaround are essential. In any printing process, the substrate plays a crucial role in determining the final print quality, and it contributes nearly 60 to 70 percent of the total cost of the printed product. Several commonly used paper-based substrates are widely employed across different inkjet press systems for producing inkjet printed outputs. The surface characteristics and optical properties of these papers influence their compatibility with specific printing processes and help in achieving improved print quality. Among the various print quality parameters, solid ink density is regarded as one of the most important indicators, as it strongly affects the overall appearance and quality of printed products. From both visual and measurable perspectives, solid ink density is expected to match standard or reference values or at least remain within an optimum range to ensure enhanced print performance. This paper focuses on analysing the relationship between the surface properties of different paper substrates commonly used in various inkjet printing systems and the optimization of solid ink density. The objective is to achieve print quality that meets standard and reference requirements, which remains a primary expectation of the printing industry.

**Keywords:** inkjet, solid ink density, paper, gloss, brightness, print quality factor, process colour.

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## 1. INTRODUCTION AND BACKGROUND

Inkjet printing is a digital printing method and is categorized under Non-Impact Printing (NIP) technologies. In this process, extremely fine ink droplets are expelled through nozzles to form an image. The printed output is produced by placing these microscopic ink drops accurately on a flat substrate surface (Kipphan, 2001). In the present time, digital printing presses particularly inkjet systems have become increasingly popular due to their efficiency and flexibility. The proper use and control of printing technology is essential for achieving high-quality printed results. Print quality is generally assessed using several important parameters such as solid ink density, dot gain, hue error, print contrast, print-through, ink trapping, and ink drying time. Among these factors, solid ink density is considered one of the most critical and widely used indicators for evaluating print quality worldwide (Bajpai, 2018a). When observing a printed sheet, the human eye perceives different colours and tonal variations, which are largely influenced by the amount of ink deposited on the paper surface. To measure colour characteristics and ink density accurately as per standard requirements, instruments such as densitometers, spectrophotometers, and spectro-densitometers are commonly used (Ataefard, 2015).

Inkjet printing presses use different types of printheads, and the printhead design largely determines the performance and characteristics of a particular inkjet system. Solid ink density is influenced not only by the press

configuration but also by the nature of the paper surface (Al-Rubaiey, 2009). The surface properties of paper play a key role in controlling how ink is deposited, absorbed, and retained during printing. Paper whiteness is defined by the level of red, green, and blue light reflected from the paper surface, which can be perceived by the human eye. Since printing inks are generally translucent, they allow light to partially pass through while also reflecting a portion of the incident light (X-rite, 2003). The reflected light from the printed ink layer can be quantified using appropriate measuring instruments. Therefore, when the ink film thickness on the paper surface increases, the solid ink density value also tends to rise.

Inkjet printing provides notable benefits compared to other printing techniques due to its relatively simple operating mechanism and high reliability during production (Lee *et al.*, 2005). It is also recognized for producing superior print quality because of its broad colour reproduction capability and high print density (Fadden and Kay, 1999). The overall performance of inkjet printing mainly depends on three key elements: the ink formulation, the printing system, and the substrate used (Xu *et al.*, 2004). Among all substrates, paper is considered the most important material in inkjet printing applications. Therefore, increasing attention is being given to understanding the physical and optical characteristics of paper, as these properties significantly influence the final print outcome (Moutinho, Ferreira and F, 2011). In the printing field, print density is generally defined as the intensity or depth of colour produced in the printed image (Aydemir, YeniDoğan and Özsoy, 2020). Paper surface properties may be categorized into internal and external characteristics. Internal properties include parameters such as pore size, porosity, and permeability, while external characteristics involve surface roughness and surface structure. A rougher paper surface can affect print appearance by influencing gloss, colour reproduction, and image contrast (Chen, 2009).

The optical characteristics of paper play an important role in determining the quality of the printed output, even though they may not directly affect machine runnability or printing performance. Since the paper surface remains visible in unprinted regions, it acts as the background and provides the base reflectance for the applied ink layer (Ataefard, 2015). ISO brightness is generally associated with the level of paper whiteness, and higher ISO brightness usually indicates a whiter sheet.

Paper whiteness and ISO brightness can influence print density to a certain extent; however, beyond a particular level, their effect on the colorimetric values of the printed image becomes negligible (Hu *et al.*, 2017). Overall, the optical attributes of paper significantly contribute to the final appearance and perceived quality of the printed product (Tong, Wu and Provatas, 2006). Additionally, papers with high opacity improve readability by minimizing show-through, allowing the front side to be read clearly without interference from printing on the reverse side (Bajpai, 2018b).

To obtain high image resolution in inkjet printing, the printing substrate should rapidly absorb aqueous ink droplets while minimizing excessive spreading of the ink on the surface. For improved print density and surface gloss, the colourants (either dye-based or pigment-based) should remain as near to the substrate surface as possible rather than penetrating deeply into the material (Gong, Fleming and Sonmez, 2010). When inkjet printing is carried out on porous substrates such as paper, it becomes important to consider two key phenomena: the lateral spreading of the ink droplet across the surface and the extent to which the ink penetrates into the substrate structure (Krainer, Smit and Hirn, 2019). Brightness is an optical property that mainly represents the reflectance in the blue region of the visible spectrum, while it does not account for reflectance in the green and red wavelength ranges. It is typically measured on a scale from 0 to 100, where a value of 100 indicates maximum brightness. However, two materials having identical brightness values may still appear noticeably different to the human eye due to differences in overall spectral reflectance (Jurič *et al.*, 2013).

High-quality printing can be achieved when the substrate possesses desirable characteristics such as high brightness, smooth surface texture, uniform spectral reflectance, and a neutral shade. In particular, the quality of paper substrates plays a vital role in determining the overall print output. Surface gloss influences the appearance of printed colour by altering the manner in which light is reflected from the ink layer (Al-Rubaiey, 2009).

The type of paper used has a strong impact on print quality, as different papers produce variations in average optical density. Studies have indicated that increased paper roughness and gloss can reduce optical density, whereas higher whiteness tends to support better density values (Ataefard, 2015). Additionally, substrates that are rough and porous

generally require a greater ink supply to achieve acceptable coverage. The amount of ink transferred onto the substrate during the printing process is therefore a crucial factor, particularly for successful reproduction of process colours (Baral and Joshi, 2016). Moreover, coating chemistry also affects colour performance. Cationic-coated surfaces show improved absorption of anionic dye-based inks compared to anionic surfaces, resulting in enhanced print quality (Lamminmäki, Kettle and Gane, 2011). Furthermore, surface irregularities caused by paper roughness can directly influence colour density and reduce the uniformity of printed output (Ha, Park and Kim, 2019).

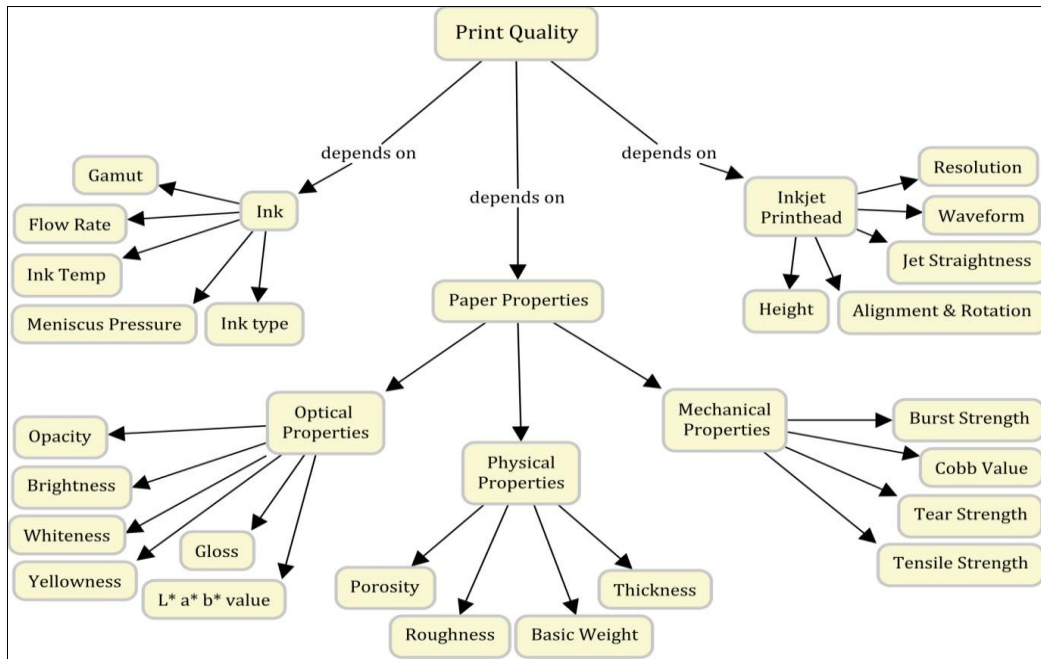


Figure 1: Schematic diagram of factor affecting print quality

Inkjet technology is considered one of the most advanced and rapidly growing areas in the printing industry; therefore, maintaining and controlling print quality parameters is highly important.

Figure 1 presents a schematic representation of the major print quality factors that influence the output quality of inkjet printing. For conventional printing processes, well-established print standards have already been developed and are widely implemented to ensure consistent and reliable print quality. However, since inkjet printing is a relatively newer technology, international standards specifically designed for inkjet systems are still in the process of research and development.

Due to the maturity and widespread acceptance of conventional printing standards, these existing standards were taken as reference guidelines in this study for evaluating solid ink density in inkjet printing. The main objective of this research is to examine the relationship between the surface characteristics of different paper grades commonly used in various inkjet printing systems and to optimize solid ink density in order to achieve improved and high-quality print results.

## 2. EXPERIMENTAL

### 2.1 Materials and Testing of Sample

In the present study, three commonly used categories of paper were chosen for evaluation. For each paper category, four different brands were collected and analysed in a certified paper testing laboratory by following standard testing procedures. Various paper characteristics were measured to assess the surface properties, including grammage or basis weight (ISO 536), brightness (ISO 2470-1), gloss (ISO 8254), and surface roughness (ISO 8791-2). Based on the test results, three paper types of 90 gsm were selected, as their measured values were found to be close to standard specifications.

These paper types included Gloss Coated (GC; paper type 1), Matt Coated (MC; paper type 2), and Uncoated (UC; paper type 3). Additionally, to study the effect of grammage on printing performance, a 115-gsm paper of the same brand was also included in the investigation.

Table 1: Properties of different types of papers

Sr. No.	Paper properties	Gloss Coated	Matt Coated	Uncoated
1	Brightness (%)	83.5	83.1	81.1
2	Gloss (%)	98.4	56.5	36.4
3	Roughness (ml/min)	10.8	12.5	15.1

Table 1 presents the measured values of various paper properties, determined using appropriate test methods in accordance with ISO standards. Solid ink density was evaluated using an X-Rite eXact spectrophotometer.

2.2 Procedure

In this study, three commonly available commercial inkjet printing systems: Continuous Inkjet (CIJ), Piezoelectric Inkjet (PIJ), and Thermal Inkjet (TIJ), were used for printing the selected paper samples. The pressroom environment was controlled and maintained according to standard pressroom specifications.

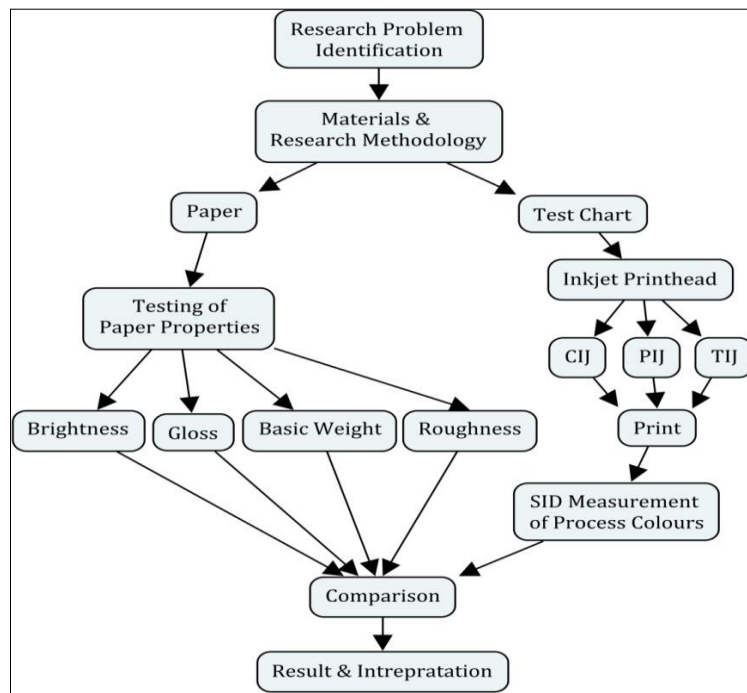


Figure 2: Schematic diagram of research methodology

A test master was specially designed for inkjet printing in accordance with relevant standards. Using this prepared test master, printing was carried out on the selected paper substrates using properly calibrated inkjet presses. Solid ink density values were then recorded with the help of a calibrated spectrophotometer. The obtained results were statistically analysed and presented through clear and informative graphical representations.

3. RESULTS

To analyse the obtained results, appropriate statistical techniques were applied to the collected data. Table 2 presents the relationship between solid ink density and the basic weight of paper. The association between solid ink density

(SID) and paper properties was determined using the Pearson correlation (two-tailed) test, where **r** represents the Pearson correlation coefficient and **p** denotes the probability value at the selected level of significance.

*Table 2: Correlation of solid ink density with basic weight*

<b>Correlations</b>					
	K	C	M	Y	Basic Weight
K	1	.893**	.891**	.708**	.156**
C		1	.862**	.771**	.178**
M			1	.623**	.125**
Y				1	.102**
Basic Weight					1

\*\* . Correlation is significant at the 0.01 level (2-tailed).

The test in table 2 has shown that the SID of black ink positively significant ( $r = .156, p < 0.01$ ). The SID of cyan was also positive significant ( $r = .178, p < 0.01$ ). Similarly, the SID of magenta and yellow ink was also positive significant ( $r = .125, p < 0.01$ ;  $r = .102, p < 0.01$ ) respectively.

*Table 3: Correlation of solid ink density with paper properties*

<b>Correlations</b>							
	K	C	M	Y	Roughness	Brightness	Gloss
K	1	.894**	.935**	.699**	-.863**	.922**	.710**
C		1	.862**	.752**	-.818**	.842**	.712**
M			1	.610**	-.957**	.949**	.881**
Y				1	-.464**	.566**	.292**
Roughness					1	-.970**	-.949**
Brightness						1	.843**
Gloss							1

\*\* . Correlation is significant at the 0.01 level (2-tailed).

\* . Correlation is significant at the 0.05 level (2-tailed).

The table 3 has shown the test results. The description of the results is discussed in the discussion section.

Figure 3 presents the graphical representation of the average solid ink density (SID) for individual inks obtained from different inkjet printing engines on various paper stocks.

For black ink (K), as shown in Figure 3(a), the TIJ system produced comparatively higher SID values across all paper types, indicating consistent performance regardless of the substrate used. In contrast, the PIJ system exhibited maximum SID on matte coated paper, while it recorded the lowest SID values on gloss coated as well as uncoated paper.

For cyan ink (C), illustrated in Figure 3(b), the CIJ system achieved higher SID values on gloss coated paper, whereas moderate SID results were observed on matte coated and uncoated paper stocks.

The PIJ system again showed higher SID on matte coated paper but produced minimum SID on gloss coated and uncoated papers. Among all the print engines, TIJ generated the highest SID on uncoated paper. However, it provided moderate SID on gloss coated paper and the lowest SID on matte coated paper.

For magenta ink (M), as shown in Figure 3(c), CIJ demonstrated superior SID performance on gloss coated paper, while moderate values were obtained on matte coated and uncoated substrates.

PIJ displayed maximum SID on matte coated paper but resulted in comparatively lower SID values on gloss coated and uncoated papers. TIJ achieved the highest SID on matte coated paper among all the systems. It produced moderate SID on gloss coated paper and nearly similar SID values on uncoated paper.

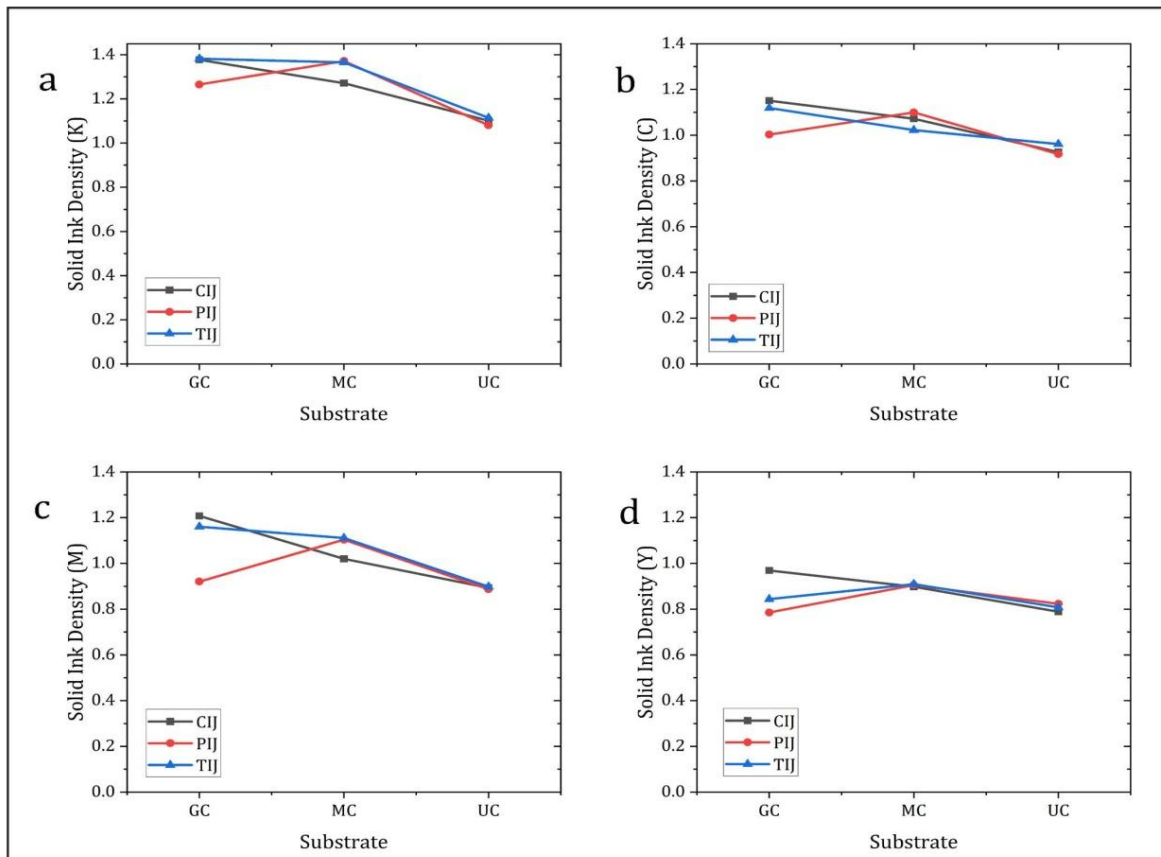


Figure 3: Solid ink density of inks on different papers using various inkjet printheads

For the solid ink density (SID) of yellow (Y), as illustrated in Figure 3(d), the CIJ printhead produced the best SID results on gloss coated paper. However, for matt coated paper, its SID values were found to be nearly comparable with those obtained from other inkjet printheads, while the lowest SID was observed on uncoated paper stock. In contrast, the PIJ printhead exhibited medium SID performance on both gloss coated and uncoated papers. Among all the printheads, the TIJ system achieved the highest SID on uncoated paper. It delivered an average SID on gloss coated paper, whereas the lowest SID was recorded on matt coated paper.

#### 4. DISCUSSION

##### a) Inkjet printheads and SID

Depending on the printing methods, the printouts may have varying degrees of quality. The print quality might vary widely from machine to machine. Similarly, inkjet printheads vary in their print quality because printheads have the major role in inkjet printing presses. Figure 4, 5 and 6 shows the performance of inkjet printheads on paper in context to solid ink densities of process colours for CIJ, PIJ and TIJ respectively. Figure 4 represents very clearly that gloss

coated paper has better SID value followed by matt coated and uncoated paper with highest value of 1.41 for Black, 1.17 for Cyan, 1.23 for Magenta and 0.98 for yellow ink.

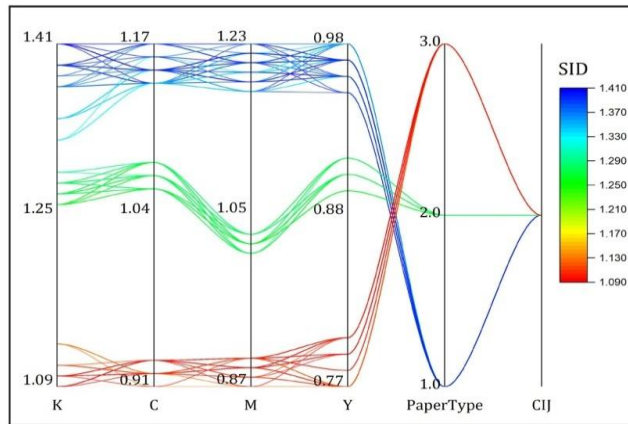


Figure 4: Performance of Continuous inkjet printhead and Solid ink density

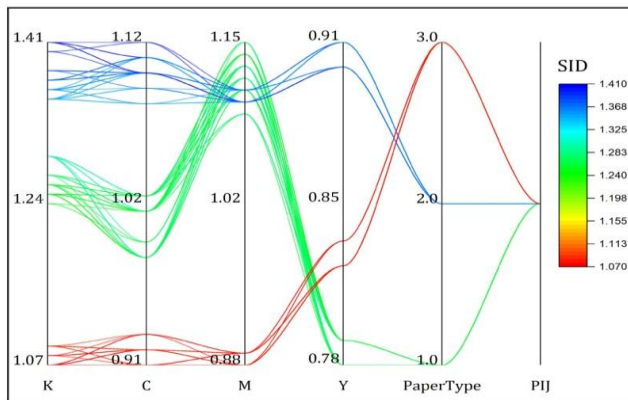


Figure 5: Performance of Piezoelectric inkjet printhead and Solid ink density

Figure 5 represents the performance of PIJ for SID on different papers. Here, SID on matt coated paper is high for black (1.41), cyan (1.12) and yellow (0.91) except magenta where gloss coated paper has highest value of SID at 1.15. The gloss coated paper has least value of SID for yellow ink at 0.78.

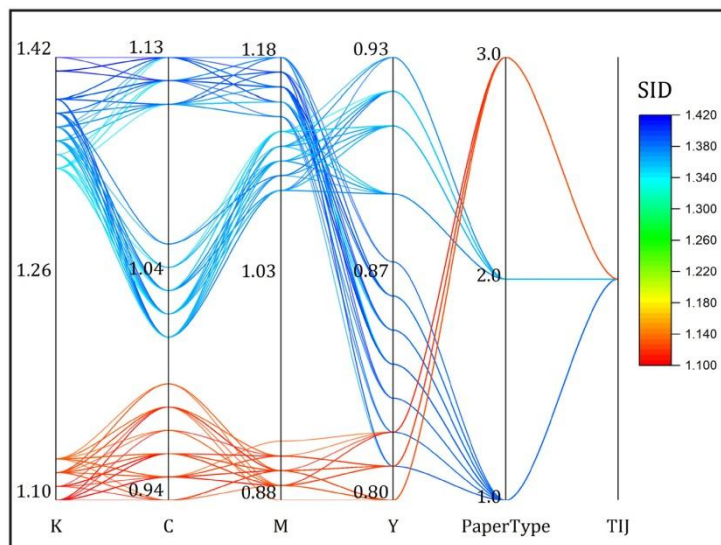


Figure 6: Performance of Thermal inkjet printhead and Solid ink density

Figure 6 represents the performance of TIJ on different papers. Uncoated paper has lowest SID values for all the process colours. The gloss coated paper has high SID value for black, cyan and magenta ink but yellow has highest value of SID on matt coated paper.

**b) Association of Basic Weight and SID**

The results indicate that the basic weight of paper has a positive relationship with solid ink density (Table 2). Black ink density shows a positive correlation with paper basic weight ( $r = 0.134, p < 0.01$ ). In the same manner, cyan ink density is also found to be positively and significantly correlated with basic weight ( $r = 0.265, p < 0.01$ ). Magenta and yellow inks also exhibit significant positive correlations with paper basic weight, with correlation values of ( $r = 0.257, p < 0.01$ ) and ( $r = 0.078, p < 0.01$ ), respectively.

This analysis clearly suggests that paper samples of 115 gsm generally produce higher solid ink density values compared to 90 gsm samples across all three inkjet printing engines. However, the strength of correlation observed between basic weight and solid ink density remains relatively low.

**c) Correlation of brightness and SID**

The brightness of paper is reflectance of blue light from the paper surface. Table 3 shows that print density increases with the increase in brightness.

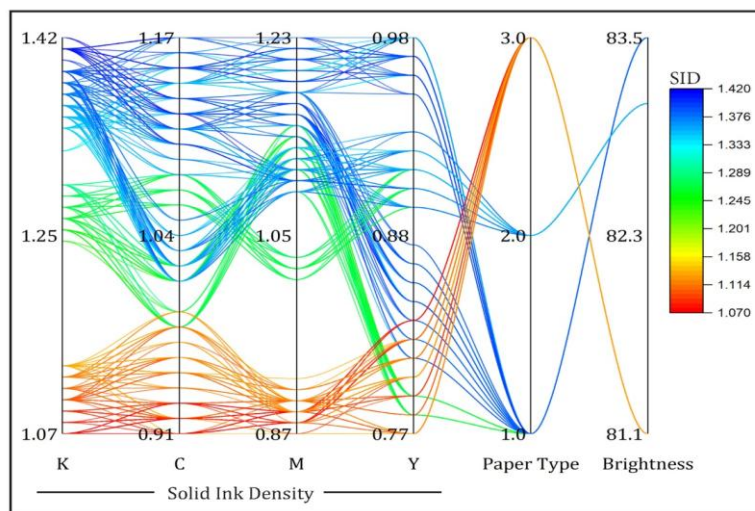


Figure 7: Correlation between Solid ink density and brightness of paper

Paper brightness refers to the ability of the paper surface to reflect blue light. As indicated in Table 3, an increase in paper brightness results in a corresponding rise in print density. A strong positive correlation was observed between black ink density and brightness ( $r = 0.922, p < 0.01$ ). In the same manner, cyan ink density also showed a significant positive relationship with brightness ( $r = 0.842, p < 0.01$ ). Magenta and yellow ink densities were also found to be positively and significantly correlated with paper brightness, with correlation values of ( $r = 0.949, p < 0.01$ ) and ( $r = 0.566, p < 0.01$ ), respectively.

Figure 7 illustrates that paper type 3 exhibited the lowest brightness and consequently produced lower solid ink density values. In contrast, paper type 1 showed higher brightness and achieved higher solid ink density. The matte coated paper demonstrated intermediate brightness, and therefore its solid ink density values also remained between the higher and lower ranges. This variation can be attributed to the smoother and brighter surface of gloss coated paper compared to uncoated paper. Furthermore, greater fluctuations in solid ink density were observed in gloss and matte coated papers as compared to uncoated paper.

**d) Correlation of gloss and SID**

Paper gloss is influenced by the way light reflects from the paper surface when it is exposed to illumination. As indicated in Table 3, black ink density shows a strong positive relationship with paper gloss ( $r = .710, p < 0.01$ ). In

the same manner, cyan ink density is also significantly and positively correlated with gloss ( $r = .712, p < 0.01$ ). Furthermore, magenta and yellow ink densities also exhibit statistically significant positive correlations with paper gloss, with correlation values of ( $r = .881, p < 0.01$ ) and ( $r = .292, p < 0.01$ ), respectively.

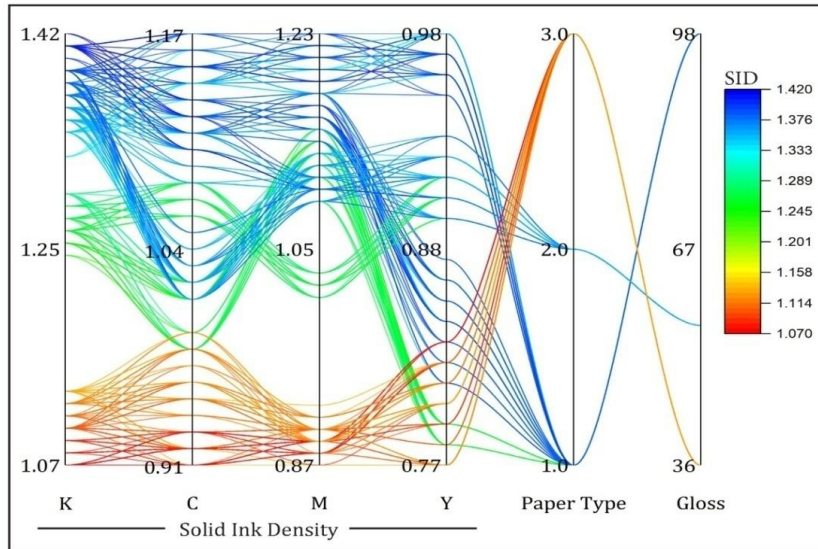


Figure 8: Correlation of gloss and solid ink density

Figure 8 shows that if the value of gloss is high for paper type 1 which results in high value of SID for gloss coated paper whereas paper type 3 has least gloss value which finally results in lower value of SID for all KCMY ink. The SID increases with increase in gloss property of the paper. The gloss property has positive influence on print density.

**e) Correlation of roughness and SID**

Paper roughness indicates the extent to which the surface of a paper is uneven or textured. Surface smoothness is an important property, as it strongly influences the final print quality. The results presented in Table 3 show that black ink density has a strong and significant negative correlation with paper roughness ( $r = -0.863, p < 0.01$ ). Likewise, cyan ink density also demonstrates a significant negative relationship with roughness ( $r = -0.818, p < 0.01$ ). In the case of magenta and yellow inks, the ink density values also exhibit statistically significant negative correlations with paper roughness, with correlation coefficients of ( $r = -0.957, p < 0.01$ ) and ( $r = -0.464, p < 0.01$ ), respectively.

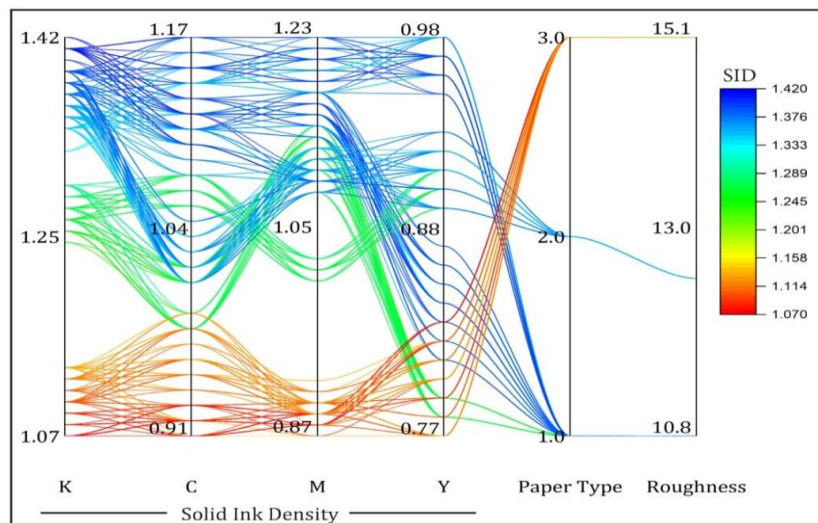


Figure 9: Correlation between Solid Ink Density and Roughness of paper

Figure 9 illustrates the relationship between solid ink density (SID) and paper roughness. It can be observed that SID decreases as the surface roughness of the paper increases for all CMYK inks. The roughness values recorded for gloss coated, matt coated, and uncoated papers were 10.8, 12.5, and 15.1 respectively (Table 1). Among these, gloss coated paper (Paper Type 1, as shown in Figure 9) exhibited the lowest roughness compared to the other paper categories.

In papers with a rougher surface, ink initially fills the uneven surface structure and then tends to penetrate into the substrate. As a result, increased roughness leads to reduced solid ink density. Since uncoated paper has the highest roughness, it shows the lowest SID values. Therefore, the results clearly indicate that gloss coated paper produces higher solid ink density, whereas uncoated paper results in the lowest SID across all inkjet printhead types.

## 5. CONCLUSION

In the present study, solid ink density (SID) was evaluated for different paper grades, including gloss coated, matt coated, and uncoated papers, using commonly employed inkjet printing systems. Key paper characteristics such as grammage (basic weight), brightness, gloss, and surface roughness were considered during the analysis. The findings indicate that the basic weight of the selected paper grades has a comparatively minor influence on SID, which may be attributed to the stronger effect of other paper properties. In addition, paper brightness was found to have a clear and strong positive relationship with solid ink density. It has been observed that papers with higher brightness generally produce higher solid ink density (SID) across different paper grades. Among the various substrates, gloss-coated paper consistently provides greater print density on all inkjet printing engines when compared with other paper types. In contrast, uncoated papers tend to absorb more ink due to higher penetration, which results in reduced print density. Consequently, solid ink density decreases as the paper surface becomes rougher and more absorbent. The findings of this study indicate that gloss-coated paper achieves superior print density in inkjet printing when compared to matte-coated and uncoated papers.

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