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QUANTITATIVE ASSESSMENT OF PRINT ATTRIBUTES IN RECYCLED AND VIRGIN PAPER: IMPLICATIONS FOR SUSTAINABLE PRINTING

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ABSTRACT
Sustainability imperatives are redefining material selection strategies across manufacturing industries, including the printing sector. Recycled paper has progressively evolved from an environmentally preferable substitute to a technically competitive substrate capable of meeting stringent print performance requirements. Historically, recycled grades were associated with low-quality print, fibre degradation and variability in mechanical strength. These limitations restricted their adoption in high-quality commercial printing applications. UV-inkjet printer is used; to print on recycled and virgin paper and both are uncoated paper. This research evaluates the influence of paper type in print quality by analysing Solid Ink Density (SID) and ink trapping behaviour for CMYK inks. A comparison between recycled and virgin paper shows that recycled paper yields higher SID values for cyan and magenta, indicating greater ink absorption, while virgin paper performs better for yellow and black, suggesting improved ink holdout. In terms of trapping, virgin paper demonstrates relatively higher efficiency across all colour combinations, whereas recycled paper provides comparable results with slightly lower values. From a performance perspective, recycled paper ensures more consistent and stable ink transfer, while virgin paper offers better optical density and overprint quality. The results confirm that print quality depends on the balance between ink absorption and surface retention. Therefore, recycled paper is suitable for applications requiring consistency and sustainability, whereas virgin paper is preferred where higher colour strength and trapping efficiency are important.

Key words — *Recycled fibre, Sustainable printing, Print performance, Packaging substrates, Solid ink density (SID), Ink trapping.*

I. INTRODUCTION

The global printing industry is experiencing structural transformation driven by sustainability regulations, resource conservation concerns and circular economy initiatives. Traditionally, virgin fibre-based paper derived from freshly processed wood pulp has been preferred for high-quality printing applications due to its superior fibre length, bonding capacity and predictable surface properties [1]. Virgin substrates offer consistent mechanical strength, controlled porosity and stable ink interaction behaviour, making them suitable for offset, gravure, flexographic and digital printing systems.

However, increasing awareness regarding deforestation, carbon emissions and waste generation has shifted industry focus toward recovered fibre utilization. The environmental footprint of virgin pulp production, including energy-intensive pulping and bleaching operations has encouraged adoption of recycled alternatives. Recycled paper is produced from post-consumer and post-industrial waste [2].

In print quality comparison of the uncoated virgin and uncoated recycled paper is deeply analysed in terms of consistency and the spectrophotometric value, the performance of virgin paper is better in Sid, and in recycled paper the ink trapping value in virgin paper demonstrates relatively higher efficiency across all colour combinations, whereas recycled paper provides comparable results with slightly lower values. From a performance perspective, these findings will help to understand which type of paper can be used for which kind of printing application can be better and also helps to know what advancements needed to get desired print quality.

1.1 Inkjet printing

The Inkjet printing is rapidly gaining attention for its variable, consistent and high quality of printing, UV printing is one step more than solvent and water-based inkjet printer, these inks dry instantly by UV light exposure, Inkjet printing is considered a highly versatile digital deposition method in which tiny droplets of material are placed onto selected areas of a surface without any physical contact. The origins of inkjet technology can be traced back to 1948, when Siemens Elema in Sweden introduced an early inkjet device that made use of the Rayleigh instability principle, in which a continuous liquid stream naturally breaks into droplets [5]. During the early 1960s, research by Sweet at Stanford University demonstrated that applying controlled pressure pulses could generate droplets of consistent size and spacing. In the following decade, IBM initiated significant research efforts to adapt this continuous-droplet concept for commercial printing applications.

Depending on the method of ejecting droplets, the inkjet printing technologies are categorized into the continuous inkjet (CIJ) and Drop on Demand (DOD) inkjet systems.

1. Continuous Inkjet (CIJ)

In CIJ systems, the printhead produces a steady stream of droplets by subjecting the ink to rapid vibrations. Each droplet receives an electrical charge, after which it passes through an electrostatic field that directs selected droplets toward the substrate to form the image. Droplets that are not needed are diverted into a collection channel and recirculated. Because droplet generation never stops, CIJ printers operate at very high speeds and can print on a wide range of materials, including curved or non-porous products such as metal cans, plastic bottles, cables and similar items. However, this method requires a more elaborate fluid system and tends to generate more unused ink due to constant droplet production.

2. Drop-on-Demand (DOD)

Unlike CIJ, DOD systems eject droplets only when the image demands them. This approach improves ink efficiency and image precision. Two main principles are used:

● Thermal DOD

A miniature heater inside the print chamber rapidly warms a small volume of ink, forming a bubble that expands and pushes a droplet out of the nozzle. This method is widely used in desktop and office printers.

● Piezoelectric DOD

A piezoelectric element changes shape when voltage is applied, generating a pressure pulse that ejects the ink. Because this mechanism accommodates a wider selection of inks including UV-curable, solvent-based, latex and pigment formulations it is commonly used in industrial and large-format printers.

Types of Inks Used in Inkjet Printing

Inkjet printing relies on fluid formulations tailored to form stable droplets and create consistent images on different substrates. The inks commonly fall into three categories first is water-based (aqueous) Inks These inks use water as the principal carrier and contain dyes or pigments along with a surfactant to maintain fluidity, they are widely used in home printers and high-quality graphic applications because of their colour vibrancy and low environmental impact. Second is Solvent-Based Inks Here, organic solvents replace water as the main vehicle. These inks bond effectively with non-absorbent surfaces such as PVC, vinyl and various plastics, producing highly durable prints. Their major drawback is the emission of volatile organic compounds (VOCs), which raises environmental and safety concerns. Third is UV curing inks, these inks dry rapidly when exposed to UV-light, it can also be used for porous surfaces because before excessive penetration the ink dry if we use UV-light at correct time [6]

1.2 Recycled paper

The recycling of paper leads to noticeable changes in both its physical characteristics and printing behaviour, primarily due to repeated fibre processing. With each recycling cycle, cellulose fibres undergo shortening and structural damage, which weakens inter-fibre bonding and reduces strength properties such as tensile, tear and burst strength. Additionally, the paper structure becomes more open and porous, increasing its absorbency. This results in greater ink penetration and higher dot gain during printing, ultimately lowering image sharpness and overall print quality. Recycled paper also tends to exhibit reduced brightness, often appearing slightly grey or yellow because of residual inks, lignin content and other impurities [3]. The presence of contaminants like adhesives and filler residues can further disrupt surface uniformity and lead to inconsistent printing results. Due to continuous fibre degradation, paper fibres can only withstand a limited number of recycling cycles generally around five to seven after which they become too short to produce strong and durable paper.

In papermaking, fillers are typically inorganic mineral materials incorporated to enhance optical characteristics, improve print performance and lower production costs. Among these, calcium carbonate is the most widely used and is available in two main forms: ground calcium carbonate (GCC) and precipitated calcium carbonate (PCC), both of which contribute to increased brightness, opacity and surface smoothness. Kaolin clay, also known as China clay, is another commonly used filler; its plate-like particle structure helps in improving surface uniformity and print quality, particularly in coated grades of paper. Talc is utilized for its hydrophobic properties and its effectiveness in controlling pitch and sticky contaminants in recycled pulp, which aids in better machine operation. For premium and specialty paper applications, titanium dioxide is preferred due to its superior brightness and opacity, although its higher cost limits widespread use. Overall, the selection of fillers significantly influences the surface properties and visual quality of paper products [4].

II.RESEARCH OBJECTIVE

This research aims to evaluate the differences of print attribute between virgin paper and recycled paper.

The primary objectives of this research are as follows:

- To obtain the measurements of printing attributes - solid ink density, ink trapping for the 100% virgin paper and recycled papers
- To identify the range of difference of print quality attributes in the 100% virgin paper and recycled papers.

1.1 Experimental Equipment and room conditions (room temp, pressure, humidity)

For measuring the print attributes X-Rite spectrophotometer is used with M0 filter.

Experimental Room conditions (according to the ISO-187):

Room temp - 24°C

Pressure - 1.01Atm

Humidity - 50% [7]

Paper Sample specifications

Specifications	Recycled Paper	Vergin Paper
Colour	White	White
Sample size	210 x 297 mm	210 x 297 mm
GSM	80	80
Brightness	65%	85%
Opacity	80%	75%

Printing machine specifications

Machine Name	Supported Paper size	Ink type	Viscosity (Ford cup)
Konika Minolta Accurojet 30000	585 x 750 mm (B2+)	UV curing ink	12-14 cP

III. DATA COLLECTION

Closely analysed the SID and Ink trapping values in 50 samples of each printed sheet of virgin and recycled paper. These data are measured by x-rite spectrophotometer in normal room condition in D50 light at spectrometer filter of M0 [8]

The test sample contain relevant test elements - SID bar and ink trapping element, sample is printed by UV-curing ink from digital inkjet printer.

1.1Printing attributes Measurement

1) **SID:** Dot gain is the increase in halftone dot size or tonal value during printing compared to the original dot size. Dot gain mainly occurs due to ink spreading and absorption in inkjet so it is important to calculate if we compare printing of100%virgin and blended recycled paper different types of paper [9].

Solid Ink Density (SID) is calculated as $D = \log_{10}(1/R)$, where R is the reflectance of the printed surface. It indicates the amount of ink present and is used to control print quality.

Measured Data using spectrophotometer

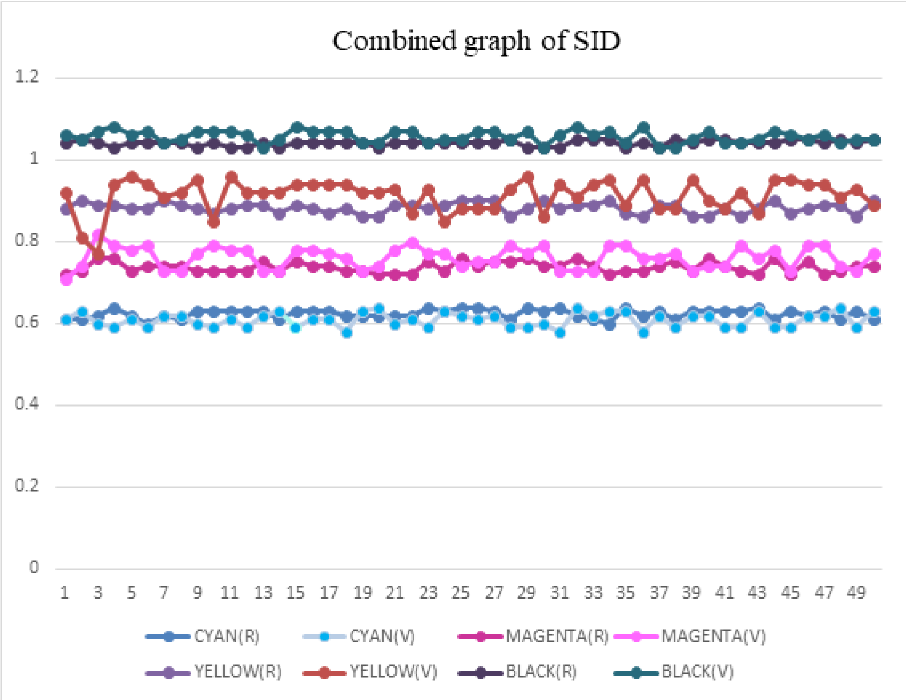

FIG: 1.1

2) **Ink Trapping:** Ink trapping is the ability of a second ink to properly print and adhere on top of a previously printed wet ink it is important to measure because it tells us how well one ink sticks on another ink, this tells correct secondary colours and affects colour strength.

Ink trapping is calculated using Preucil's formula: Trap (%) = $(D_{12} - D_1)/D_2 \times 100$, where $D_{12}$is overprint density, $D_1$is first ink density and $D_2$is second ink density. It indicates the efficiency of ink transfer in multicolour printing [10].

Measured Data using spectrophotometer

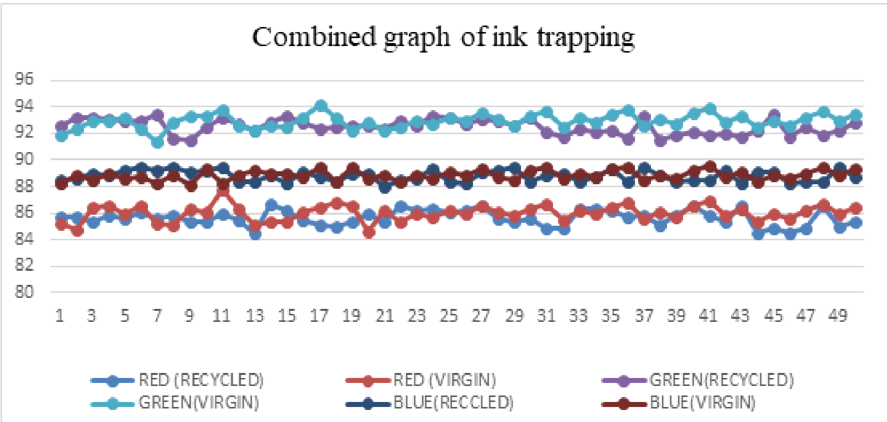

FIG: 2.1

Observations

The Fig: 1.1 is the graph of SID values of CMYK for recycled and virgin paper.

CYAN COLOUR	Virgin paper	Recycled paper
Max value	0.64	0.64
Min value	0.60	0.58
Average	0.609	0.624
MAGENTA COLOUR		
Max value	0.82	0.76
Min value	0.71	0.72

Average	**0.761**	**0.738**
YELLOW COLOUR		
Max value	**0.9**	**0.96**
Min value	**0.77**	**0.8**
Average	**0.912**	**0.882**
BLACK COLOUR		
Max value	**1.08**	**1.05**
Min value	**1.03**	**1.03**
Average	**1.057**	**1.040**

Table: 1.3

The Fig: 2.1 is the graph of Ink trapping values for recycled and virgin paper.

Magenta + Yellow = Red	Virgin paper	Recycled paper
Max value	**86.9**	**86.7**
Min value	**84.8**	**84.5**
Average	**86.024**	**85.658**
Cyan + Yellow = Green		
Max value	**94.1**	**93.3**
Min value	**94.1**	**91.5**
Average	**92.938**	**92.516**
Cyan + Magenta = Blue		
Max value	**89.1**	**89.5**
Min value	**88.1**	**88**
Average	**88.860**	**88.798**

Table: 2.2

According to the graphical data from figure 1.1 and table 1.3:

- The Sid of cyan in recycled paper is higher than the virgin paper, in magenta colour recycled paper has greater Sid value than the virgin paper, in yellow colour Sid value of virgin paper is higher than the recycled paper and in black colour the Sid value is higher in virgin paper than the recycled paper.
- The consistency of cyan colour is higher than the other colours, in case of cyan colour only the recycled paper shows more consistency than the virgin paper, in case of magenta colour recycled paper has more consistency in values than the virgin paper, in yellow consistency of both the recycled and virgin paper is almost same, in black colour
- Consistency of the recycled paper is more than the virgin paper.
- The difference (virgin paper- recycled paper) of Sid value of cyan between virgin and recycled paper is -0.015, in case of magenta difference is 0.023 in case of yellow difference is 0.030 and in black colour difference is 0.017.
- The average Sid value of black is highest then among all, second highest is yellow colour and third is magenta and the least value is obtained by cyan colour, this observation is valid for both recycled and virgin paper.

According to the graphical data from figure 2.1 and table 2.2

- The trapping value of yellow over magenta in virgin paper is higher than the recycled paper, value of yellow over the cyan is more in the virgin paper than the recycled paper, trapping of magenta over cyan is higher in virgin paper than recycled paper.
- Ink trapping Consistency in case of yellow over magenta is better in recycled paper than the virgin paper, in case if yellow over cyan consistency is almost same in both paper but in higher virgin paper than recycled paper with small value, in case of magenta over cyan the trapping consistency is almost same in virgin and recycled paper.
- The consistency of magenta over cyan is highest among other trappings, in second position consistency of yellow over cyan stands and the least consistent trapping is yellow over magenta.
- The difference of ink trapping between Virgin and Recycled paper, for yellow over magenta difference is 0.366, for yellow over cyan difference is 0.422, for magenta over cyan difference is 0.062

- Ink trapping of yellow over cyan has highest value, second is magenta over cyan and yellow over magenta has the lowest trapping value, this observation is valid in case of both recycled and virgin paper.

IV. RESULT

- The evaluation of Solid Ink Density (SID) highlights clear substrate-driven differences in ink–paper interaction mechanisms. Recycled paper shows relatively higher SID values for cyan and magenta, which can be attributed to increased ink absorption and a more porous surface structure. Conversely, virgin paper exhibits higher SID for yellow and black, indicating better surface holdout and more effective optical response for these inks.
- In terms of process uniformity, recycled paper demonstrates improved consistency, particularly for cyan, magenta and black, suggesting more stable ink transfer and reduced variability during printing. For yellow ink, both substrates display nearly equivalent consistency, implying limited sensitivity to substrate characteristics.
- The overall variation in SID between the two paper types remains marginal, indicating that both recycled and virgin papers deliver comparable print performance, with minor differences arising from specific ink–substrate interactions such as absorption behaviour, ink spreading and surface energy effects.
- The observed density sequence (Black > Yellow > Magenta > Cyan) is consistent with established optical density principles, where inks with higher pigment loading and light absorption capacity produce greater density values, independent of the substrate used.
- The analysis of ink trapping behaviour indicates that **virgin paper consistently achieves higher trapping values** for all colour combinations (yellow **over magenta, yellow over cyan and magenta over cyan)** compared to recycled paper. This suggests that virgin paper provides better ink transfer efficiency and interlayer adhesion, likely due to improved surface characteristics such as smoother structure and controlled absorbency.
- From a **consistency standpoint**, recycled paper demonstrates better uniformity for **yellow over magenta trapping**, while for **yellow over cyan and magenta over cyan**, both substrates show nearly comparable consistency, with a slight advantage observed for virgin paper in the case of yellow over cyan. Overall, the variation in consistency between the two substrates remains minimal for most trapping combinations
- Among all trapping sequences, **magenta over cyan exhibits the highest consistency**, followed by **yellow over cyan**, whereas **yellow over magenta shows the least consistency**, indicating greater variability in this ink interaction.
- The magnitude of trapping differences between virgin and recycled paper is most significant for **yellow over cyan**, followed by **yellow over magenta**, while **magenta over cyan shows only a minor difference**, suggesting that this combination is less sensitive to substrate variation.
- Furthermore, the general trapping hierarchy (**Yellow over Cyan > Magenta over Cyan > Yellow over Magenta**) is consistent for both paper types, reflecting inherent differences in ink film formation, wetting behaviour and overprint interaction.

V. CONCLUSION

Recycled paper Favors absorption and consistency, while virgin paper favors optical density and trapping efficiency. Therefore, the selection of paper should be based on the desired outcome process stability and sustainability (recycled paper) versus maximum colour quality and print sharpness (virgin paper).

both substrates are suitable for printing applications. Recycled paper offers advantages in terms of process stability and environmental sustainability, while virgin paper provides slightly enhanced optical density for certain ink colours. Therefore, the selection of substrate should be guided by the desired balance between print quality, consistency and sustainability considerations.

Virgin paper provides higher ink trapping efficiency; recycled paper offers comparable performance with acceptable consistency levels. Therefore, both substrates are suitable for printing applications, virgin paper being preferable for achieving maximum trapping efficiency and recycled paper being a viable alternative where sustainability considerations are important.

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