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SUSTAINABLE INKJET PRINTING: PRINT PERFORMANCE ANALYSIS OF ECO-FRIENDLY INKS ON PLASTIC SUBSTRATES

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ABSTRACT

Uv-curable piezoelectric inkjet technology has revolutionized wide-format printing by minimizing volatile compound emissions (VOC) released issues and high-fidelity output on non-absorbent polymeric substrates. The Greenguard Gold accreditation has emerged as the accepted standard for eco-friendly ink systems in the retail graphics, flexible packaging and indoor-outdoor advertising industries. The US EPA's NESHAP compliance and the needs of circular sustainable economy are causing the industry's rapid shift from polyvinylchloride film to easily recyclable polyester film substrates, necessitating the stringent measurable characterization of print performance difference under certified output constraints. No prior research has presented contemporaneous comparative Solid Ink Density (SID) and Tone Value Increase (TVI)/ Dot Gain data for Greenguard Gold certified UV-curable inks on both substrates under identical piezoelectric inkjet conditions across a rigorous specimen population. Under ISO-recommended measurement and process parameters, this study measures and compares SID and TVI (at 40% & 80% nominal tone) across all CMYK channels for n=50 specimen per substrates. Print samples was printed on a Mimaki UJV 100-160 Plus piezoelectric (dod) system at 1200 × 1200 dpi using Mimaki LUS-210 UV-ECO Series Greenguard Gold-Certified CMYK inks. An X-Rite eXact spectrophotometer was used to measure SID in accordance with ISO 5-3/ISO13655 (M0);TVI was quantify using the Murray-Davis equation in accordance with ISO 12647-1. PVCF & PF achieve across all CMYK channels for SID (C:1.34,M:1.35,Y:1.30,K:1.43 vs C:1.04,M:1.14,Y:1.12,K:1.25), with a mean inter-substrate difference of 0.24 D. According to TVI analysis Yellow was the highest dot gain channel on both substrates at 40% nominal tone (PVCF:31.20%; PF:26.87%) and Cyan was substantially greater on PF (16.34%) compared to PVCF (11.61%). Standard deviation values of (0.02-0.90) validated process overall reliability. These outcomes prove that substrate-specific ICC profile calibration and tone curve compensation are essential prerequisites for achieving chromatic and tonal parity with PVCF under identical conditions and also establish a statistically supported ISO-validated framework for substrate selection in UV inkjet production environments. This study contributes to five Sustainable Development Goals of the United Nations. Utilizing a low-voc Greenguard Gold-certified inks advance SDG 3 (Good Health and Well-Being ,Target 3.9) by removing toxic air pollutants (toluene, xylene and ethyl acetate) that are categorized under US EPA NESHAP. SDG 7 (Affordable and Clean Energy, Target 7.3) is supported by UV-LED curing, which uses 50-70% less energy than traditional mercury-arc systems. SDG 9 (Industry, Innovation and Infrastructure , Target 9.4) is in line with the use of ISO-validated piezoelectric DOD inkjet as a clean industrial process. SDG 12 (Responsible Consumption and Production, Targets 12.4 & 12.6) is addressed by comparing eco-preferred PET to PVC by lowering Industrial VOC and CO2 emissions throughout the printing Industry, these actions together meet SDG 13 (Climate Action, Target 13.2).

Keywords: Sustainable Inkjet Printing, Greenguard Gold Certified UV Ink (Eco-Friendly UV Ink), Polyester Film, Polyvinylchloride Film, Print Quality (SID & TVI/Dot Gain)

1. INTRODUCTION

The globally printing and packaging industries have undergone significant changes of material selection and process design due to a transition toward sustainable manufacturing. With near-zero volatile organic compound (VOC) emissions, instantaneous photopolymerization and substrate versatility not possible traditional conventional processes, UV-curable piezoelectric inkjet technology has emerged as a technically and ecologically desirable production platform for [1] [2]. The demand for certified low-emission alternatives has increased across large & wide-format printing industries, including indoor-outdoor advertising, flexible packaging and retail graphics, as regulatory compliance such as the US EPA National Emission Standards for Hazardous Air Pollutants (NESHAP), gradually restrict the use of solvent-based ink [2] [3]. Additionally, PET film emerged as a highly stringent eco-preferred substrate that challenges the dominant position of PVC Film in wide-format applications due to demand of swap out ecologically burdensome substrates with easily recyclable polymeric substitutes [4] [5]. These substrates have basically distinct surface physiochemical profiles; PVC shows more topographic heterogeneity due to plasticizer migration, with surface energies of 36-42 mN/m and measurably grater inter-sheet variation, while PET shows surface energies of 38-44 mN/m with surface roughness Ra < 0.5 µm [6]. These discrepancies have a significant impact on the dynamics of ink-substrate wetting, dot formation and ultimately attainable chromatic and tonal accuracy of the printed product; yet their comparative quantification under certified ink and regulated production settings has not been methodically established. The two most analytically basic parameters for characterizing print quality under ISO 12647-1 and ISO 5-3 frameworks are Solid Ink Density (SID) & Tone Value Increase (TVI)/ Dot Gain [7] [8]. SID directly controls the optical absorptance of the cured ink layer and establishes the colour gamut while TVI measures halftone dot enlargement beyond nominal digital specification controlling tonal reproduction accuracy across the tonal scale. Evidence-based substrate selection and process improvement in commercial UV inkjet environments are hindered by the lack of simultaneous comparative SID & TVI data for Greenguard Gold certified UV curable inks (eco-friendly) on both substrates under identical piezoelectric inkjet production conditions across statistically reliable specimen population [9].

Here we present an empirical study of print quality performance on PVC film (PVCF) & Polyester Film (PF), printed using Mimaki 100-160 plus piezoelectric (dod) inkjet machine with Mimaki LUS-210 UV-ECO Series Greenguard Gold-certified CMYK inks. we quantify substrate driven systematic impacts and inter-specimen fluctuations, quantify SID across all CMYK channels and TVI at 40% & 80% nominal input tones over n=50 specimen per substrate and determine the physical causes behind observed print quality differentials. The outcomes directly inform the shift from PVCF to easily recyclable polymeric substrates without compromising chromatic or tonal reproduction fidelity by offering a statistically supported comparative framework for substrate selection & process control in production UV inkjet environments using certified eco-friendly ink systems.

This research centres around five of the Sustainable Development Goals (SDG's) of the United Nations' 2030 Agenda for Sustainable Development [10]. SDG 3 (Good Health and Well-Being ,Target 3.9), which calls for significant reduction of deaths and illnesses attributable to hazardous chemicals and air pollution by 2030 (Target 3.9) directly addresses the global printing industry's acknowledge contribution to VOC emissions & hazardous waste [11] [12].When compared to traditional mercury-arc UV systems, the UV-LED curing technique used in this work reduces energy usage by 50-70% making a quantifiable contribution to SDG 7 (Affordable and Clean Energy, Target 7.3) [3]. SDG 9 (Industry, Innovation and Infrastructure, Target 9.4) is immediately fulfilled by upgrading industrial printing infrastructure with piezoelectric (dod) inkjet technology and ecologically certified ink systems [10]. The principles of SDG 12 (Responsible Consumption and production, Targets 12.4 & 12.6)which require the environmentally sound management of chemicals and encourage comparative sustainable, eco-preferred or easily recyclable corporate reporting practices are operationalized by Comparing eco- preferred polyester film to conventional PVC [13]. This study supports SDG 13 (Climate Action, Target 13.2) by offering empirical ISO-Standardized baseline data that facilitates a sector-wide shift to low emission printing. This is in line with the Paris Agreement's commitments to incorporate climate changes measures into industrial policy and planning [12] [14].

2. LITERATURE REVIEW AND THEORETICAL BACKGROUND

Piezoelectric (DOD) inkjet printing uses applied voltage waveforms to deform a pressure chamber and release controlled ink droplets, achieving native resolutions of 300-1440 dpi with droplet volumes in the 2-42 pL range [8]. When exposed to UV light (365-395 nm), UV-curable inks made of acrylate or epoxide monomers, photo-initiators and pigment dispersions quickly polymerize to produce a high-density, dimensionally stable film [15]. Wijshoff modelled meniscus oscillation and satellite droplet dynamics as variables of waveform voltage & ink rheology [6]. Decker et al. showed that under-cure causes residual photo-initiator migration, surface tack and color gamut compression [16]. Surface energy, roughness (Ra) and chemistry of the substrate surface all play a crucial role in controlling the behaviour of ink deposition. PET films (surface energy 38-44 mN/m; Ra < 0.5 µm) encourages regulated dot spreading [17] [18].While PVC substrates show more heterogeneity because of plasticizer migration and calendaring texture (surface energy 36-42 mN/m),leading to increased print variance [19] [20]. ISO 12647-6 minimum regulate of 1.30 (C), 1.35 (M), 0.90 (Y) and 1.55 (K) on plastic surfaces regulates SID as determined by ISO 5-3 [21] [22]. For hydrophobic substrates, TVI is mostly optical in nature; ISO 12647-2 recommends 18% TVI at 40% nominal tone [23]. In Comparison to CIJ & TIJ on coated substrates, piezoelectric (dod) produces the lowest TVI/Dot Gain across all CMYK channels across printhead technologies, confirming the mimaki UJV100-160 Plus for UV-curable ink deposition on PVC & PET films [24]. The 40% & 80% ISO 12647-6 measurements points used for CMYK characterization on both substrates are based on TVI peaks at 40-50% nominal tone [25]. The SID & TVI differences between both substrates are supported by surface smoothness & surface energy, which are crucial factors that control color consistency & print quality in piezoelectric

DOD inkjet [26]. The SID differences observed under identical UV-curable manufacturing circumstances are supported by substrate porosity and roughness, which also control ink retention and surface density [27]. The evidence gap in certified UV-curable ink performance on eco-preferred polymeric substrates is confirmed by the fact that SID & Tonal reproduction accuracy continue to be the most critically significant print quality characteristics in DOD inkjet [28]. Saturation expectations for the UV-eco-ink used are informed by the greater grayness of UV inks on vinyl (≈ PVC) compared to latex systems [29]. Similar to the inter-substrate difference between PVC & Polyester found here, substrate surface controls ΔE [30]. The ISO 12647 approach, which benchmarks permissible dot gain ranges is mirrored in the print contrast and TVI methodology [31]. Substrates characteristics are confirmed as the main print quality variable by substrate-driven ΔE variation across five ISO paper grades [32].
A thorough review of the literature reveals that no previous study has reported at the print quality of Greenguard Gold-certified inks on PET & PVC film substrates using inkjet printing, nor has comparative inter-substrate evaluation been documented. While SID & TVI have been studied separately on selected substrates, there is still no simultaneous comparative characterization of both substrate types. The current research directly examines through rigorous print quality benchmarking under regulated piezoelectric DOD UV inkjet production conditions. Therefore, it seems that the topic of research " Sustainable Inkjet Printing: Print Performance Analysis of Eco-friendly Inks on Plastic Substrates" validate itself in coming scenario.

3. MATERIALS AND METHODOLOGY

3.1 Printing System

A Mimaki UJV100-160 Plus roll-to-roll LED-UV inkjet printer was employed, fitted with drop-on-demand piezoelectric printheads in a 2-head staggered configuration (droplet volume:7-21 pL variable dot; maximum addressable resolution: 1200 dpi). The system was run in unidirectional 16-pass mode at 1200×1200 dpi, with production speed set below the machine default to ensure consistent ink laydown, cure and print quality. A twin UV-LED lamp assembly (peak emission: 395 nm UVA; Cumulative dose adequate for full through-cure per pass), with a low-intensity pinning LED array (395 nm) integrated between passes to arrest dot spreading prior to final cure. Mimaki LUS-210 UV-ECO series CMYK + White + Clear pigmented UV-curable ink were used for throughout (viscosity: 8-12 mPa.s at 40°C; surface tension: 26-30 mN/m). Printhead temperature was held at 40 ± 1.0 °C via active thermal regulation. Prior to each substrate session and after every 10 printed sheets, automated nozzle verification was performed using the onboard NCU (Nozzle Check Unit): upon detection of defective nozzles, the NRS (Nozzle Recovery System) initiated automatic print-head cleaning to maintain consistent jetting performance throughout production [9] [33].

3.2 Printing Substrates

Table-1 Product Information Sheet (PI Sheet) [34] [35] [36] [36]**.**

PHYSICAL PROPERTIES		
Base Substrate	PVC (Polyvinyl Chloride)	100 % Polyester (Woven)
Surface Finish	Gloss	Satin Smooth
Thickness/Weight	120 Micron	130 GSM
Liner	140 GSM Silicon Release Liner	No Liner (Non-Adhesive)
Adhesive	Permanent Grey (Acrylic-Based)	None —non-adhesive
Application Type	Frontlit (Self-Adhesive Surface Mount)	Backlit (Tension Frame/ Lightbox)
ENVIRONMENTAL PROFILE		
PVC Content	PVC-Based	PVC-Free
Biodegradability	Low (PVC is non-biodegradable or difficult to recycle or complex process)	Better (Polyester easily recyclable)
Environmental Rating	Standard	Eco-Preferred

3.3 Test Form and RIP Workflow

A standardised print quality test form was designed incorporating: (a) CMYK solid density bars or patches (100% single colorant); (b) gradiation patches of CMYK from 1-100%. The test form was prepared as a PDF/X-6 file and rasterised through RasterLink7 with ISO web coated as the reference printing conditions. All 50 sheets of each substrate were printed consecutively without recalibrating to capture natural production-run variance. Sheets were sequentially numbered and then measured.

3.4 Measurement Protocol

The X-Rite eXactTM spectrophotometer meets the special requirement of colour measurement in the pressroom and ink labs. It supports all measurements modes according to ISO standards (M0,M1,M2,& M3). All measurements were performed M0: Unpolarized, no filter, UV included under an Illuminant D50 Observer Angle 2° (ISO 13655:2017) [37]. The instrument was white-calibrated before each substrate session and drift-checked after every 10 sheets using a certified traceable ceramic tile.

Two print quality parameters were extracted per sheet:

(1) Solid Ink Density (SID) measured from the 100% solid patches of each CMYK channel using a spectrophotometer under ISO 13655 M0/D50/2° observer geometry with Status T filter per ANSI PH2.18.

(2) Tone Value Increase (TVI/Dot Gain) extracted from the 40% & 80% nominal halftone patches of each CMYK channel per sheet, computed using the Murray-Davies equation per ISO 12647-1 [38].

3.5 Statistical Analysis

Descriptive statistics (minimum, maximum, mean, average and standard deviation) were computed for each parameter-substrate combination.

4. DATA COLLECTION AND ANALYSIS

4.1 Descriptive Statistics

According to the ISO 12647 series for printing process control, Solid Ink Density (SID) and Tonal Value Increase (TVI)/Dot Gain are two fundamental metrics used to measure & calibrate printed colors. To study print suitability on Polyester (PF) & Polyvinyl Chloride Film (PVCF) using Inkjet Printing (at 1200 DPI) various factors considered included Solid Ink Density (SID) and Tonal Value Increase (TVI)/Dot Gain. The results obtained from print suitability point of view are elaborated as below:

4.1.1 Solid Ink Density (SID)

Solid Ink Density is the optical measurement (using a densitometer or spectrophotometer) of the amount of light absorbed by a solid patch of an ink on a substrate. It is an indirect measure of the ink film thickness transferred onto the substrate. The data of Solid Ink Density (SID) (No. of tested sheet is 50) of Cyan, Magenta, Yellow & Black colour on Polyvinyl Chloride Film using Inkjet Printing are presented in below table-2.

Table-2 Solid Ink Density of Polyvinyl Chloride Film

SID	Cyan	Magenta	Yellow	Black
Min. Value	1.24	1.27	1.18	1.37
Max. Value	1.42	1.40	1.39	1.50
Mean Value	1.34	1.35	1.30	1.43
Avg. Value	1.34	1.35	1.30	1.43
S.D. Value	0.04	0.03	0.04	0.03

Solid Ink Density value for Cyan, Magenta, Yellow and Black on Polyvinyl Chloride Film substrates were recorded across all four process colours showed consistent print quality. Black recorded the highest mean density (1.43), followed by Magenta (1.35), Cyan (1.34), and Yellow (1.30). The low standard deviation values (0.03-0.04) and near identical mean & average value.

Again, the data of Solid Ink Density (SID) (No. of tested sheet is 50) of Cyan, Magenta, Yellow & Black colour on Polyester Film using Inkjet Printing are presented in below table-3.

Table-3 Solid Ink Density of Polyester Film

SID	Cyan	Magenta	Yellow	Black
Min. Value	0.99	1.10	1.07	1.17
Max. Value	1.09	1.19	1.18	1.30
Mean Value	1.04	1.14	1.12	1.25
Avg. Value	1.04	1.14	1.12	1.25
S.D. Value	0.03	0.02	0.02	0.03

Solid Ink Density value for Cyan, Magenta, Yellow and Black on Polyester Film substrates were recorded across all four process colours showed consistent print quality. Black achieved the highest mean density (1.25), followed by Magenta (1.14), Yellow (1.12) and Cyan (1.04). Density values ranged from a minimum of 0.99(Cyan) to a minimum of 1.30(Black). Standard deviation values were consistently low (0.02-0.03) and mean & average values were identical across all channels.

4.1.2 Tone Value Increase (TVI)/Dot Gain

TVI (formerly known as Dot Gain) is the optical phenomenon where printed halftone dots appear larger on the substrate than they do in the original digital file. It is also known as Tone Value Increase, it is the mathematically calculated as the difference between the tone value of a printed tint and the tint percentage in the digital file.

TVI= Printed Dot% - Digital Dot%.

At 40% TVI measures in Mid-Tone & track how dark or saturated the final image appear. The data of Tone Value Increase (TVI)/Dot Gain (No. of tested sheet is 50) of Cyan, Magenta, Yellow and Black colour at 40% on Polyester Film using Inkjet Printing are presented in below table-4.

Table-4 Tone Value Increase of Polyester Film at 40%

TVI at 40%	Cyan	Magenta	Yellow	Black
Min. Value	14.00	2.00	25.30	4.40
Max. Value	17.80	3.50	28.40	6.80
Mean Value	16.32	2.68	26.86	5.41
Avg. Value	16.34	2.71	26.87	5.43
S.D. Value	0.81	0.39	0.77	0.54

Tone Value Increase (TVI)/Dot Gain at 40% input for Polyester Film revealed notable variation across the four process colours. Yellow exhibited the highest mean TVI (26.86), followed by Cyan (16.32), Black (5.41), and Magenta (2.68). The widespread between the highest Yellow (26.86) and lowest Magenta (2.68) values across color channels on the substrate surface. Standard deviation values were relatively low (0.39-0.81) and mean & average values were closely aligned for all channels.

Again, the data of Tone Value Increase (TVI)/Dot Gain (No. of tested sheet is 50) of Cyan, Magenta, Yellow and Black colour at 40% on Polyvinyl Chloride Film using Inkjet Printing are presented in below table-5.

Table-5 Tone Value Increase of Polyvinyl Chloride Film at 40%

TVI at 40%	Cyan	Magenta	Yellow	Black
Min. Value	7.40	6.10	29.30	7.80
Max. Value	13.50	8.30	33.20	10.40
Mean Value	11.52	7.20	31.19	9.07
Avg. Value	11.61	7.22	31.20	9.09
S.D. Value	0.83	0.55	0.90	0.57

Tone Value Increase (TVI)/Dot Gain at 40% input for Polyvinyl Chloride Film showed considerable variation across process colours. Yellow recorded the highest mean TVI (31.19), followed by Cyan (12.04), Black (10.50) and Magenta

(9.37). Standard deviation values were low across all channels (0.51-0.78) and mean & average values were virtually identical.
At 80% TVI measures in Shadow & Dark tone areas, shadow detail retention, shadow plugging (loss of dark area detail) and check for how well dark areas are produced. Now, the data of Tone Value Increase (TVI)/Dot Gain (No. of tested sheet is 50) of Cyan, Magenta, Yellow and Black colour at 80% on Polyester Film using Inkjet Printing are presented in below table-6.

Table-6 Tone Value Increase of Polyester Film at 80%

TVI at 80%	Cyan	Magenta	Yellow	Black
Min. Value	10.60	8.00	18.00	9.10
Max. Value	13.50	10.40	20.60	11.80
Mean Value	12.04	9.37	19.15	10.50
Avg. Value	12.07	9.38	19.16	10.52
S.D. Value	0.78	0.51	0.59	0.64

After that, Tone Value Increase (TVI)/Dot Gain at 80% input for Polyester Film demonstrated a more compressed range across process colours tonal value. Yellow recorded the highest mean TVI (19.15), followed by Cyan (12.04), Black (10.50) and Magenta (9.37). Standard deviation values were low across all channels (0.51-0.78) and mean & average values were virtually identical.
Again, the data of Tone Value Increase (TVI)/Dot Gain (No. of tested sheet is 50) of Cyan, Magenta, Yellow and Black colour at 80% on Polyvinyl Chloride Film using Inkjet Printing are presented in below table-7.

Table-7 Tone Value Increase of Polyvinyl Chloride Film at 80%

TVI at 80%	Cyan	Magenta	Yellow	Black
Min. Value	13.80	11.50	18.50	11.40
Max. Value	16.20	13.40	21.00	14.00
Mean Value	14.99	12.27	19.82	12.89
Avg. Value	15.00	12.27	19.82	12.90
S.D. Value	0.55	0.33	0.51	0.56

Lastly, Tone Value Increase (TVI)/Dot Gain at 80% input for Polyvinyl Chloride Film showed a compressed but elevated range across all process colours. Yellow recorded the highest mean TVI (19.82), followed by Cyan (14.99), Black (12.89) and Magenta (12.27). Standard deviation values were notably low (0.33-0.56), with mean & average values in near-perfect agreement.

5. RESULTS AND DISCUSSIONS

The data was collected & analyzed. It was found that the mean values of Solid Ink Density (SID) & Tone Value Increase (TVI)/Dot Gain were observed in accordance with standard range of the print quality and printing technology in terms of Inkjet Printing Process. We also observed repeated value of TVI/Dot Gain & SID again and again during the present investigations. The Overall result made from the observation is that there is always consistency with Inkjet Printing either it is SID OR TVI/Dot Gain. While observing these two print quality parameters on two different types of substrates i.e. Polyester Film & Polyvinyl Chloride Film, I found that Inkjet Printing has slight variations on these substrates. Summary of the analyzed data of SID & TVI/Dot Gain is delineated in table 8, 9 and 10 respectively as below:-

Table-8 Average Value of Solid Ink Density of Polyvinyl Chloride Film & Polyester Film

Average Value of SID	Cyan	Magenta	Yellow	Black
Polyvinyl Chloride Film	1.34	1.35	1.30	1.43
Polyester Film	1.04	1.14	1.13	1.25

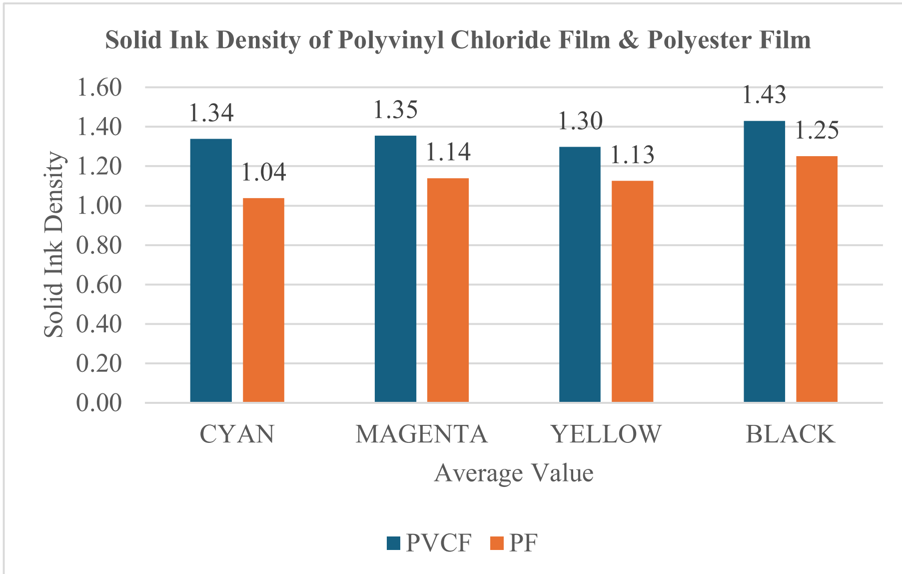

Fig-1 Average Value of Solid Ink Density of Polyvinyl Chloride Film & Polyester Film

Table-8 & Fig-1 Present the average Solid Ink Density (SID) values for CMYK channels printed on two plastic substrates i.e. Polyvinyl Chloride Film (PVCF) and Polyester Film (PF), measured according to the ISO-standard. PVCF recorded Superior SID across all channels (C:1.34, M: 1.35, Y: 1.30 & K: 1.43) relative to PF (C:1.04, M: 1.14, Y: 1.13 & K: 1.25), with a mean inter-substrate differential of 0.24 D. This disparity is attributable to the higher surface energy & smother topography of PVCF, which promotes enhanced UV ink wetting, reduced dot spread and a denser more optically compact cured ink film. Conversely, the comparatively low surface energy & micro-porous texture of PF restrict ink-substrate adhesion and lateral ink film formation, yielding measurably reduced optical density. Across both substrates, the Black(K) channel consistently produced the highest SID values, consistent with the elevated pigment volume concentration (PVC) of carbon-black-based UV inkjet formulations. Notably, all PVCF values fall within the ISO reference range whereas PF values fall below the reference range for all channels, indicating that PF requires more surface pre-treatment or ink formulations to achieve ISO-compliant solid ink density under identical UV piezoelectric printing conditions.

Table-9 Average Value of Tone Value Increase (TVI/Dot Gain) of Polyvinyl Chloride Film & Polyester Film at 40%

Average Value of TVI at 40%	Cyan	Magenta	Yellow	Black
PVCF	11.606	7.224	31.198	9.088
PF	16.34	2.708	26.87	5.434

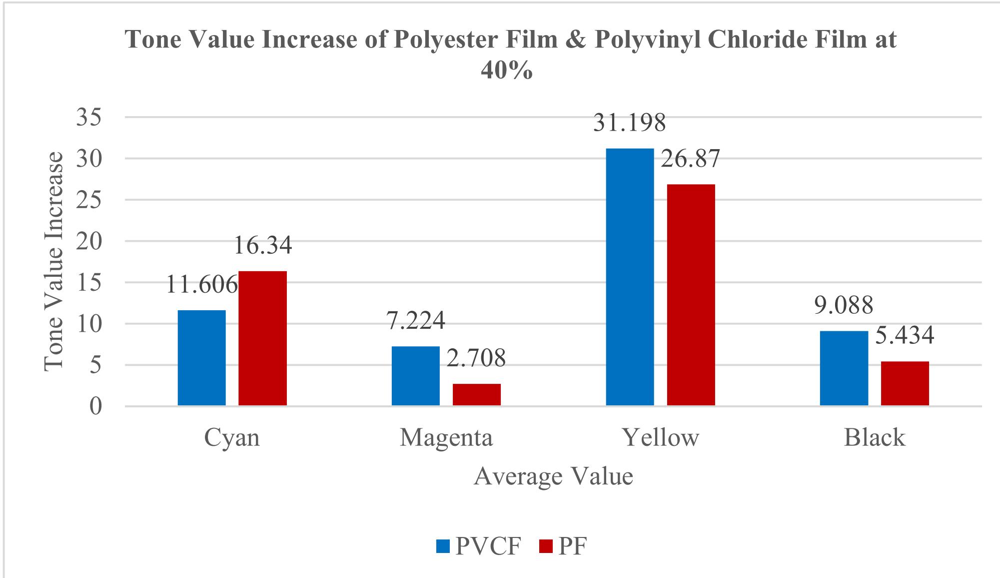

Fig-2 Average Value of Tone Value Increase (TVI/Dot Gain) of Polyvinyl Chloride Film & Polyester Film at 40%

Table-9 & Fig-2 A comparison of average TVI values at 40% between Polyvinyl Chloride Film (PVCF) & Polyester Film (PF) reveals distinct dot gain behaviour across substrates. Yellow exhibited the highest TVI on both PVCF (31.198) & PF (26.870), while Magenta recorded the lowest on PF (2.708) and the second lowest on PVCF (7.224). PVCF consistently yielded higher TVI values in Cyan (11.606 vs 16.340 – noting PF was higher here), Black (9.088 vs 5.434), and Magenta (7.224 vs 2.708), whereas PF showed greater dot gain in cyan (16.340 vs 11.606), suggesting channel-specific ink-substrate interactions. The markedly higher Cyan TVI on PF and elevated Magenta & Black. TVI on PVCF indicate that each substrate influences ink spread differently depending on the colour channel, underscoring the necessity of substrate-specific tone curve adjustments for accurate colour reproduction on flexible film materials.

Table-10 Average Value of Tone Value Increase (TVI/Dot Gain) of Polyvinyl Chloride Film & Polyester Film at 80%

Average Value of TVI at 80%	Cyan	Magenta	Yellow	Black
PVCF	15	12.27	19.82	12.9
PF	12.07	9.38	19.16	10.52

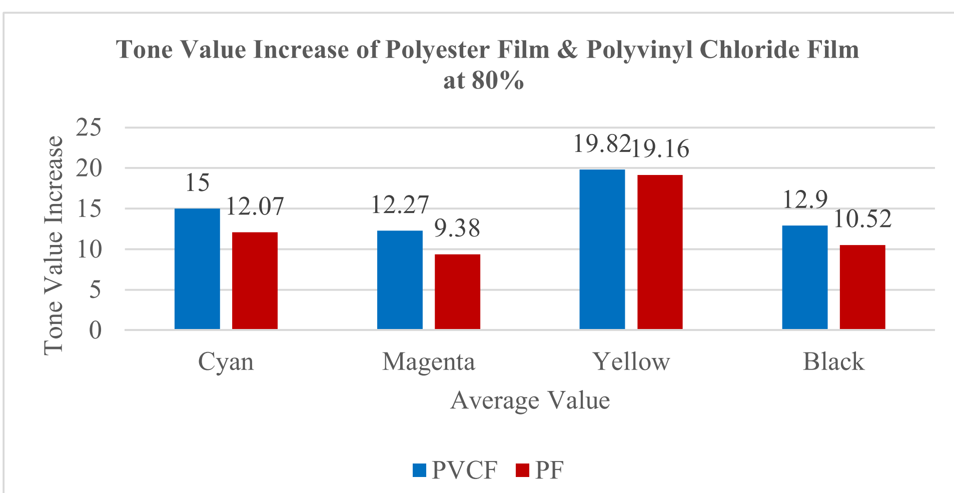

Fig-3 Average Value of Tone Value Increase (TVI/Dot Gain) of Polyvinyl Chloride Film & Polyester Film at 80%

Table-10 & Fig-3 A comparison of average TVI values at 80% between Polyvinyl Chloride (PVCF) & Polyester Film (PF) confirms that PVCF consistently exhibited higher dot gain across all four process colours. Cyan showed the greatest inter-substrate difference (15.00 vs 12.07), followed by Magenta (12.27 vs 9.38) & Black (12.09 vs 10.52), while Yellow recorded the smallest difference (19.82 vs 19.16), suggesting that ink spread in the Yellow channel is relatively substrate-independent at higher tonal ranges. Compared to 40% TVI results, the inter-channel spread narrowed considerably on both substrates at 80% consistent with the characteristic compression of dot gain in shadow tonal regions. The uniformly higher TVI on PVCF across all channels at 80% reaffirms its grater propensity for ink spread relative to PF, further emphasizing the need for substrate-specific tone compensation in flexible film printing workflows.

6. CONCLUSIONS

This study evaluated SID and TVI at 40 % & 80% nominal tone across CMYK channels on PVCF & PF substrates. PVCF consistently yielded higher SID values across all channels, with the greatest inter-substrate differential observed in Cyan (ΔSID 0.30), indicating superior blue-green reproduction & broader colour gamut. Black recorded the highest density on both substrates. Notably, tighter inter-channel density variation on PVCF (0.13 vs 0.21 on PF) reflects improved ink balance, colour consistency, confirming superior ink holdout, colour saturation & visual quality relative to PF under identical printing conditions. TVI analysis at 40% mid-tone revealed that PVCF delivers higher colour strength , it exhibits greater dot gain in Yellow, Magenta & Black channels producing warmer, heavier tonal rendition in printed output . PF demonstrates lower colour strength but superior control in Yellow & Black, yielding improved tonal neutrality. Elevated Yellow TVI on both substrates remained the dominant factors affecting colour balance, introducing a warm colour bias across the printed output. TVI analysis at 80% shadow & dark tone areas, PVCF proved superior for high-density, wide-gamut, high-contrast output , though at the cost of greater dot gain particularly in Yellow, where shadow-regions dot expansion compromised tonal accuracy. PF exhibited lower density but superior dot gain control, affording improved tonal stability & shadow detail preservation. The highest inter-substrate TVI differential was recorded in Cyan (2.93%), manifesting a shadow heaviness and loss of details in dark blue regions on PVCF, against cleaner tonal transitions on PF. Collectively, PVCF is optimised for visual impact & colour strength; PF for shadow detail, tonal accuracy & process stability. The findings of this study extend beyond print quality characterisation to provide empirical support for five UN sustainable Development Goals. ISO-complaint SID & TVI performance with Greenguard Gold-certified UV inks validates VOC-free formulations as viable solvent-free replacements, advancing SDG 3 (Target 3.9). The UV-LED curing platform delivers 50-70% energy reduction versus mercury-arc system, supporting SDG 7 (Target 7.3). The established eco-certified piezoelectric inkjet performance baselines facilitate cleaner production adoption per SDG 9 (Target 9.4). The environmentally sound management of chemicals and encourage comparative sustainable, eco-preferred or easily recyclable corporate reporting practices are operationalized by Comparing eco- preferred polyester film to conventional comes under SDG 12 (Target 12.4, 12.6) and advances sustainable circular economy transition. Collectively, these findings underpin the evidence base for decarbonisation-oriented policy frameworks in industrial printing, contributing to SDG 13 (Target 13.2).

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