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Taguchi's Grey Relationship Analysis (GRA) for Comparing the Performance of Various Inkjet Printheads for Tone Value Increase on Uncoated Paper Substrates

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Abstract— Digital technologies in printing attract more attention among the printers in recent years. All around the world, inkjet technology is used by both home and commercial printers. New applications for inkjet printing have emerged as the technology has developed, including the printing of high-quality periodicals and the packaging sector. This state-of-the-art technology, particularly Inkjet, has undergone extensive testing and refinement to ensure high quality prints High-quality printing often makes use of gloss coated sheets. Yet the high price of gloss coated paper limits its usefulness to certain types of work. Since then, it has been clear that uncoated papers are the best option for this task. The print quality would be different from that of glossy coated paper because of the roughness, porosity, and unevenness of the surface. Tone Value Increase (TVI) on uncoated paper printed with various inkjet printheads is an intriguing topic for investigation. Therefore, effective TVI is crucial. Multiple commercial inkjet printheads were tested for their TVI performance on uncoated paper and the results were compared using a novel statistical approach Taguchi's Grey Relational Analysis (GRA). The use of this statistical method yielded fruitful results in our study.

Keywords— print quality; inkjet printhead; tone value increase; uncoated; grey relational analysis.

I. INTRODUCTION

Types of Inkjet Printing are based on its printhead structure. There are two main categories of inkjet printing presses, distinguished by the kind of printhead they use: Continuous inkjet and Drop-on-Demand inkjet [1]. Because of surface tension forces, the nucleated droplets created by inkjet printers are spherical, meaning that even the tiniest feasible dot will be round [2]. Paper is by far the most widely used printing substrate, and it plays a crucial part in the whole printing industry. Both coated and uncoated papers are widely available. All three of these factors—technology, ink, and paper—impact the quality of a final printed output [3]. If the dot gain of print is bigger than the actual value, the inks must have spread throughout the paper, making the dot area a quantitative indicator of print quality. TVI and ink spreading degrades print quality [4]. Because of specific properties of the papers, TVI analysis is the most important component when printing with inkjet printheads. This study focuses on use of a novel statistical method called Taguchi’s Grey Relational Analysis (GRA) to analyse the performance of different inkjet printheads on commonly used uncoated paper in relation to dot gain.

II. REVIEW OF LITERATURE

The optical dot gain results from the ink spreading and penetrating the paper, whereas the physical dot gain is generated by the paper's porous structure. Commonly referred to as the "Yule-Nielsen effect," this result is the optical dot gain. The optical dot gain comes from internal paper light scattering [5,6,7]. The Yule Nielsen Spectrum Neugebauer equation was used to the problem of modelling a printer, and the results showed that the typical spectral root mean squared error was 0.59 percent, and the typical colour error was 1.54 E*ab [8]. One of the most popular and straightforward halftone reflectance models is Murray-Davies [9]. Utilizing the Murray-Davies equation with the Yule-photon Nielsen's adjustment, most Dot gain values were calculated and analysed. As the research shows, inkjet papers offer superior surface qualities over non-inkjet sheets due to their lower levels of dot gain. Dot gain for inkjet sheets peaks at around 40%-50% tint, the same as for non-inkjet materials [4,10]. Dot gain was investigated by Chu and Li, who used Grey Relational Analysis to determine how different paper qualities affected dot gain [11].

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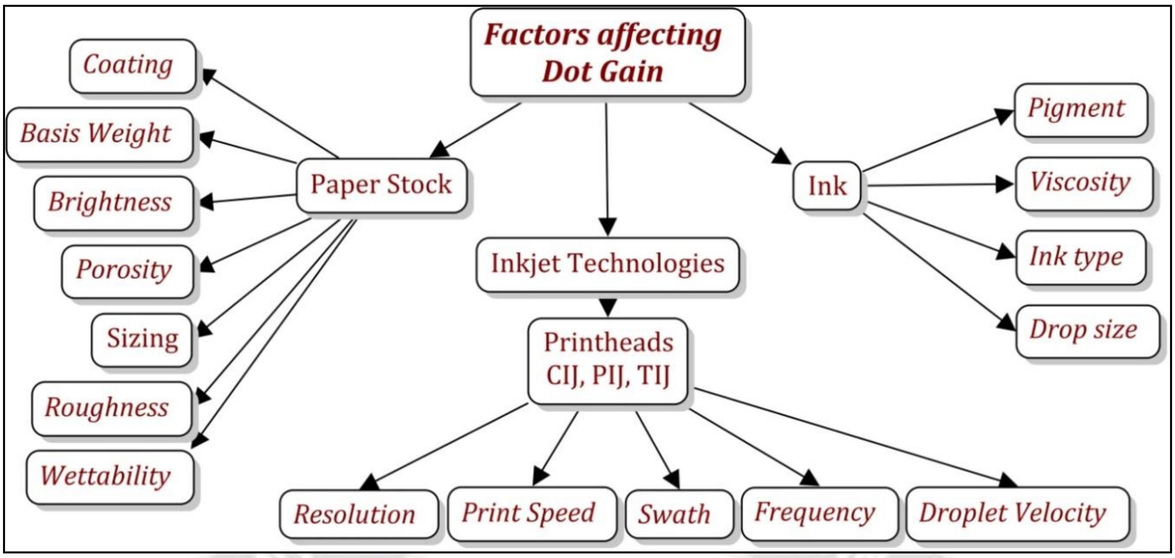

Figure 1: Some importance variables influence tone value increase in inkjet printing [12]

Dot gain is very sensitive to the degree of paper porosity [13]. Inkjet dot sizes and shapes are very sensitive to substrate properties, especially coating type [2]. In addition, the accuracy with which the dots are put on the paper determines how sharp the resulting image will be. $CaCO_3$ has a higher dot gain than SiO_2 does, just as the coatings on various papers have varied values [14]. There should be a good amount of ink still on the surface after printing for optimal dot reproduction, since less ink will penetrate deeper into the paper. If there is a lot of ink already on the surface, wetting will produce dot gain [15]. The keys to successful printing are low dot gain and a circular dot shape. The surface is very smooth, which helps maintain uniformity in dot size and shape. As expected, calendared-coated paper substrates exhibited decreased dot gain values. Dot gain was unaffected by variations in coating pigment mixes [16]. Tone value increases were found to be negligible when printed on uncoated paper. Coated papers have higher dot gains because their surface coatings increase the gain per dot. Flat surfaces, however, provided a more stable environment for dots [7]. Dot gain during inkjet printing on paper is affected by a number of variables, some of which are seen in Figure 1.

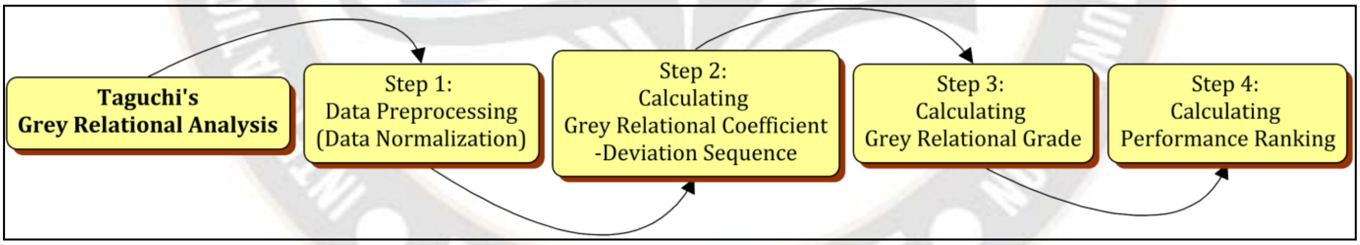

Figure 2: Sequential evolution of Grey Relational Analysis (GRA) equations [12]

In 1982, the Grey System was conceived for the first time. In 1989, Deng Julong introduced the Grey Relationship Analysis (GRA) statistical method [17]. In addition to its many applications, this theory is also efficiently used to decision making, grey target models, control systems and models [18] and this idea has been effectively used in a variety of fields, including education, business, manufacturing, electronic equipment, and mechanical engineering, among others [19]. It has come to light that the Grey Relational Analysis was used seldom in the evaluation of print performance and quality criteria. Figure 2 depicts the sequential evolution of GRA equations.

III. OBJECTIVE OF THE RESEARCH WORK

The inkjet printing technology is quickly rising in popularity among the many forms of digital printing. It is crucial, then, to compare the quality of output from various inkjet printheads on uncoated paper. One of the most crucial aspects to focus on is tone value increase. Therefore, this research work is based on the following hypothesis: (H1) when using digital inkjet printing technology, uncoated paper does not experience TVI; if H1 false then, (H2) when it comes to TVI on uncoated paper material; both continuous inkjet and Drop-on-Demand inkjet printheads provide consistent results; (H3) no significant impact of TVI on print quality in inkjet printing.

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IV. MATERIALS & METHODOLOGY

To achieve the goal of the study, commonly available uncoated paper of 90 g/m^2 was considered. Authentic scientific testing was performed on four different kinds of paper to determine their relative parameters properties. After extensive testing, a single variety of paper was chosen due to its values being so close to the standard value. Table 1 displays the measured values.

Table 1: Assessing the qualities of uncoated paper

Sr. No.	Paper properties	Gloss Coated
1	Brightness (%)	81.1
2	Gloss (%)	36.4
3	Roughness (ml/min)	15.1
4	Opacity (%)	91.0
5	Porosity (ml/min)	155.1

Standard printing settings were used to print on the chosen paper using three distinct inkjet printheads (CIJ, PIJ, and TIJ). The printing press was set at temperature of 25° C and relative humidity of 55% during press run. The completion of the TVI objective was included into the master test chart. Standard viewing circumstances were used to get readings from a calibrated x-rite eXact advanced spectrophotometer on colour patches with 25, 50 and 75% dot percentage values. The process that was used to carry out this investigation is shown in Figure 3.

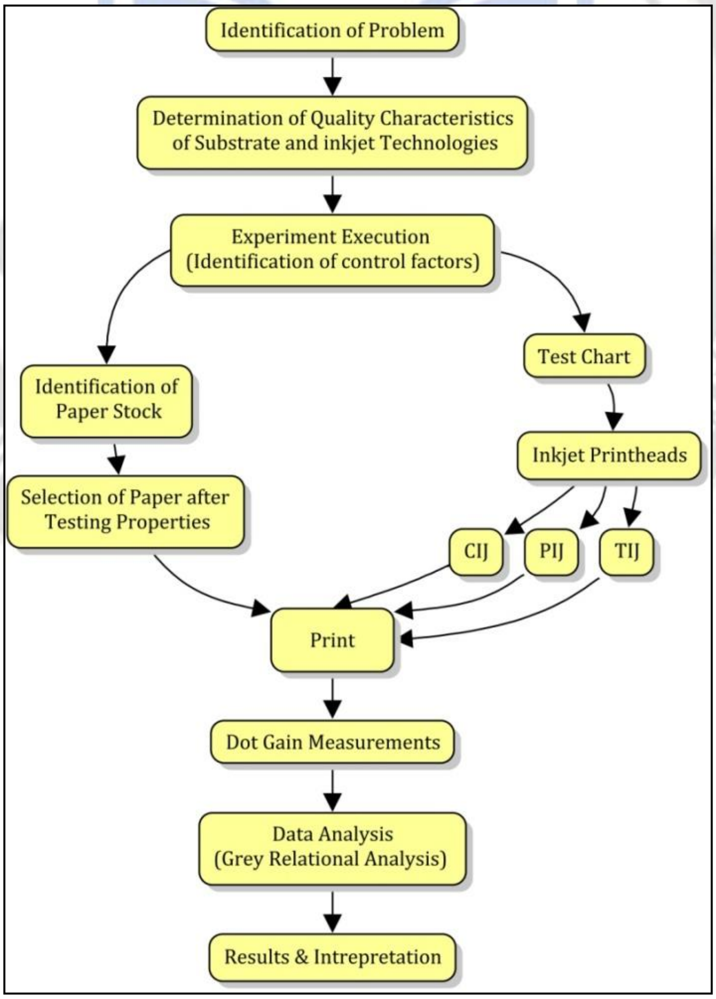

Figure 3: Diagrammatic representation of the research methodology [12]

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GRA procedures need careful attention to detail while doing computations. The process includes the following steps - (i) Data Preprocessing, (ii) Grey Relational Coefficient, (iii) Grey Relational Grade and (iv) Performance Ranking.

Step 1: Data Pre-processing

The first stage in processing data involves "normalizing" the information. In order to do this conversion, either equation (1) or (2) may use. When the data suggests that a greater value is associated with a more desirable quality, equation (1) should be applied. In cases when low values are preferred or non-beneficial characteristics are being measured, it is appropriate to apply equation (2).

Beneficial attributes (higher is better):

$$x_i^*(k) = \frac{x_i^o(k) - \min x_i^o(k)}{\max x_i^o(k) - \min x_i^o(k)} \quad \text{……. (1)}$$

Where, $X_i{*}_I$ (k) = value obtained after the grey relational generation

min $x_i(k)$ = lowest value of $x_i(k)$ for the k^{th} response

max $x_i(k)$ = highest value of $x_i(k)$ for the k^{th} response

Non-Beneficial Attributes (lower is better):

$$x_i^*(k) = \frac{\max x_i^o(k) - x_i^o(k)}{\max x_i^o(k) - \min x_i^o(k)} \quad \text{…… (2)}$$

Where,

$X_i{*}_I$ (k) = value obtained after the grey relational generation

min $x_i(k)$ = lowest value of $x_i(k)$ for the k^{th} response

max $x_i(k)$ = highest value of $x_i(k)$ for the k^{th} response

Step 2: Grey Relational Coefficient

a. Deviation Sequences: The sequence of deviations may be determined by solving a given equation.

$$x_i^*(k) = 1 - \frac{\left| x_i^o(k) - x_i^o \right|}{\max x_i^o(k) - x_i^o} \quad \text{………... (3)}$$

b. Grey Relational Coefficient: The Grey relational coefficient can be determined as follows:

$$\xi_i(k) = \frac{\Delta\min + \xi\Delta\max}{\Delta_{0j}(k) + \xi\Delta\max} \quad \text{……… (4)}$$

Where; Distinguished Coefficient (ξ) lies in between 0 and 1. Here, we are taking its value as 0.5.

Δmin- minimum value obtained from Deviation sequence

Δmin- minimum value obtained from Deviation sequence

Δ_{0j} –absolute value difference between the target sequence and comparison sequence

Step 3: Grey Relational Grade:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} w_k \xi_i(k) \quad \text{………. (5)}$$

Where,

n= quantification of process responses

ξi(k) = Grey relational coefficient

ω_k (k) is 1 (Weight).

In the end, Grey Relational Analysis was used to evaluate and visually depict the acquired data.

V. DATA COLLECTION & ANALYSIS

The TVI values at various positions were measured using a calibrated x-rite eXact spectrophotometer under controlled lighting conditions. Using a spectrophotometer, we determined the value of TVI at 25% dot area (Highlight side), 50% dot area (Middle tone) and 75% dot area (Shadow tone) of the printed test chart. The median values (in percentage) of TVI at 25%, 50%, and 75% dot area are provided in Table 01. The TVI by different printheads CIJ, PIJ, and TIJ are represented in Table 02.

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Table 02: Measured tone value increase reading

Print heads	25 % Dot Area				50 % Dot Area				75 % Dot Area			
	K	C	M	Y	K	C	M	Y	K	C	M	Y
CIJ	11.97	12.85	15.02	13.10	15.76	18.77	20.34	15.32	10.52	15.33	18.04	13.14
PIJ	17.08	10.08	10.02	11.89	22.92	14.13	13.19	13.19	15.98	12.64	12.80	14.41
TIJ	16.46	13.50	15.48	13.27	20.67	15.54	17.33	16.55	15.51	13.74	15.14	14.32

Step 1: Preprocessing of data

Data Normalization: In the printing process, TVI is a negative (less is more) quality. Thus, an equation (2) was used to transform the data into a normalized format. TVI values for 25%, 50%, and 75% dot area have been normalized between 0 and 1 as shown in Table 03.

Table 03: Normalized form of data shown in Table 02

Print heads	25 % Dot Area				50 % Dot Area				75 % Dot Area			
	K	C	M	Y	K	C	M	Y	K	C	M	Y
CIJ	1	0.190	0.085	0.127	1	0	0	0.366	1	0	0	1
PIJ	0	1	1	0.104	0	1	1	0.203	0	1	1	0
TIJ	0.121	0	0	0	0.314	0.695	0.420	0	0.086	0.590	0.554	0.006

Step 2: Grey Relational Coefficient Calculation

a) Determining the Deviation Sequence: The Grey Relational Coefficient may be derived from the value of the deviation sequence. Since values for the calculated deviation sequences using equation (3) is shown in Table 04.

Table 04: Sequence of Deviation Calculation

Printheads	25 % Dot Area				50 % Dot Area				75 % Dot Area			
	K	C	M	Y	K	C	M	Y	K	C	M	Y
CIJ	0	0.810	0.915	0.873	0	1	1	0.634	0	1	1	0
PIJ	1	0	0	0.896	1	0	0	0.797	1	0	0	1
TIJ	0.879	1	1	1	0.686	0.305	0.580	1	0.914	0.410	0.446	0.994

b) Calculation of the Grey Relationship Coefficient: The Grey Relational Coefficient was computed using equation (4). In this case, 1 is the highest and 0 is the lowest possible score, while 0.5 is the Distinguished Coefficient (ξ). The values of the Grey Relational Coefficient are shown in Table 05.

Table 05: Grey Relational Coefficient for TVI at different dot area

Printheads	25 % Dot Area				50 % Dot Area				75 % Dot Area			
	K	C	M	Y	K	C	M	Y	K	C	M	Y
CIJ	1	0.382	0.353	0.364	1	0.333	0.333	0.441	1	0.333	0.333	1
PIJ	0.333	1	1	0.358	0.333	1	1	0.386	0.333	1	1	0.333
TIJ	0.363	0.333	0.333	0.333	0.422	0.621	0.463	0.333	0.354	0.549	0.528	0.335

Step 3: Calculating Grey Relational Grade (GRG)

During the process of evaluating the components that contribute to the TVI print quality, a value of ω_k (k) that was similar to 1 was believed to be a standard for the black, cyan, magenta, and yellow inks. In order to calculate the Grey Relational Grade at this point, equation (5) is used. The values that were acquired for the grey relational grade are shown in Table 06.

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Table 06: Grey Relational Grade obtained from Table 05

Printheads	25% Dot area	50% Dot area	75% Dot area
CIJ	0.700	0.703	0.889
PIJ	0.897	0.906	0.889
TIJ	0.454	0.613	0.589

Step 04: Grey Relational Analysis-based ranking of printheads

The rankings of the various printheads according to their dot gain performance are shown in Table 07.

Table 07: Ranking of performance of Printheads

Printheads	25% Dot area	50% Dot area	75% Dot area
CIJ	2	2	1
PIJ	1	1	1
TIJ	3	3	3

VI. RESULTS & DISCUSSION

The TVI is a crucial indication of print quality. It is difficult to completely eradicate, but it is not insurmountable either. Figure 4 provides a visual representation of the data measured for black ink in Table 02. It has been shown that TVI for all three inkjet printheads lies below the ISO 12647-2 standard values for black ink. Amongst these inkjet printheads, piezoelectric inkjet has shown least value of TVI at 25%, 50% ant 75% dot area. CIJ has shown more value of TVI than other two inkjet printheads. TIJ has shown the TVI value intermediate to the other two inkjet printheads.

Figure 5 has shown the graph of TVI measured by different inkjet printheads on uncoated paper for cyan ink. The dotted line has shown the value of ISO 12647-2 standard values for reference. Figure 5 has shown that PIJ has lowers the value of TVI at 50% and 75% dot area but little higher at 25% dot area with reference to standard value (dotted line). PIJ has shown overall least value of TVI when compare to TIJ and CIJ inkjet printheads. TIJ has shown value of TVI below the standard dotted line at 75% dot area but it is highest at 50% dot area. CIJ has highest value at 25% and 75% dot area but below to TIJ at 50% dot area.

Figure 6 has shown the graph of TVI measured by different inkjet printheads on uncoated paper for magenta ink. The dotted line has shown the value of ISO 12647-2 standard values for reference. Figure 6 has shown that PIJ has close to standard line of TVI at 25% and 50% dot area but little higher at 75% dot area with reference to standard value (dotted line). TIJ has shown value of TVI higher to the standard dotted line at 25% and 50% dot areas but it is lowest at 75% dot area. CIJ has highest value at 25% and 50% dot area but below to PIJ at 75% dot area.

Figure 7 has shown the graph of TVI measured by different inkjet printheads on uncoated paper for yellow ink. The dotted line has shown the value of ISO 12647-2 standard values for reference. Figure 7 has shown that PIJ has lowers the value of TVI at 25%, 50% and 75% dot areas but little higher at 25% dot area with reference to standard value (dotted line). PIJ has shown overall least value of TVI when compare to TIJ and CIJ inkjet printheads. TIJ has shown value of TVI below the standard dotted line at 75% dot area but it is lower to standard line at 75% dot area. CIJ has highest value at 25%, 75% and 50% dot areas.

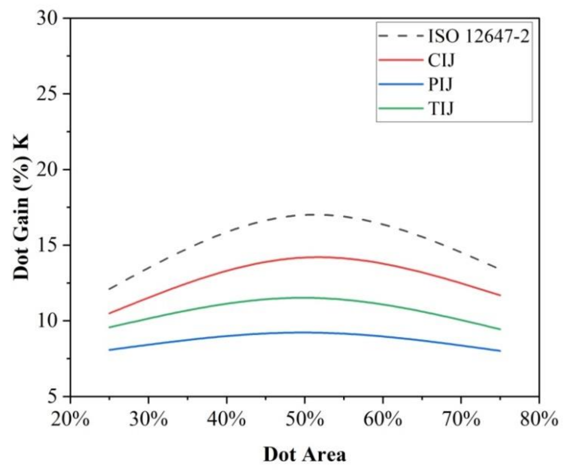

Figure 4. TVI of black ink on uncoated paper by different inkjet printheads

The Taguchi's Grey Relational Analysis approach results that shows ranking by placing PIJ at first, CIJ at second and TIJ at third (Table 07). The GRA tool has shown the ranking of CIJ and PIJ for 75% dot area at one. Since, droplets in CIJ move at such a high speed, they may penetrate deeply into the paper and result in a considerable lot of TVI. In thermal inkjet (TIJ), droplets volume may extend from nozzles during a heat mechanism, which implies that they may be extremely hot and therefore can produce more TVI on the paper material [20].

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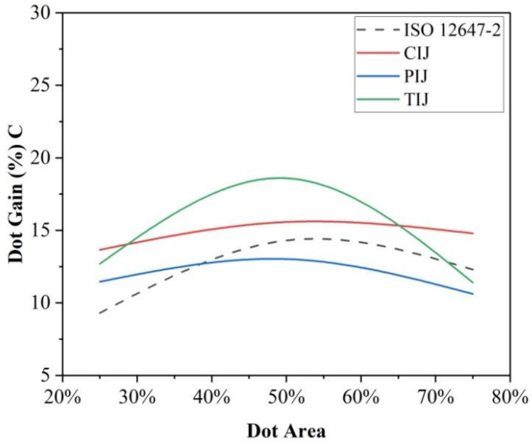

Figure 5. TVI of cyan ink on uncoated paper by different inkjet printheads

In case of PIJ, the zirconate titanate (often used) crystal experiences a piezoelectric action when an electric current is transmitted through it. Since no heat is utilised, the drop velocity may be accurately managed, may lessen the TVI in the uncoated paper material.

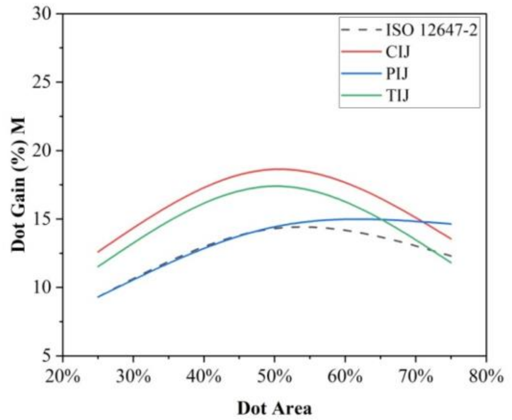

Figure 6. TVI of magenta ink on uncoated paper by different inkjet printheads

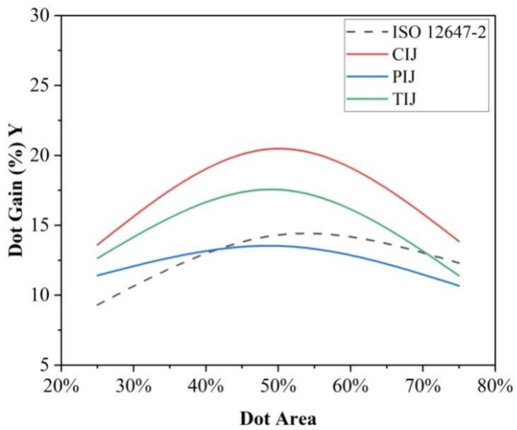

Figure 7. TVI of yellow ink on uncoated paper by different inkjet printheads

VII. CONCLUSION

From the findings of the aforementioned investigation, it was concluded that piezoelectric inkjet printhead performed best in the 25%, 50%, and 75% dot zones. With the second rating, continuous inkjet printheads perform better than TIJ but worse than piezoelectric inkjet printheads. Since, PIJ and CIJ have showed equal effectiveness at 75% dot area. When compared to other TVI methods, TIJ's performance and overall score placed it in third place. However, when printing on uncoated papers, various considerations, such as the ink type, the ink viscosity, the speed of drop ejaculation, the resolution, and the paper-ink interactions, must be made when deciding on a printhead. The Grey Relational Analysis is the most reliable statistical tool for investigating the myriad of factors that impact print quality. It has the potential to serve as a trustworthy tool for making the best possible decisions in the printing sector.

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