A Green and Practical Color Photograph Printing Technology Based on Color Difference Model and Human Perception

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ABSTRACT As all kinds of self-contained display products have become popular, various technologies for improving printing applications have gradually been ignored or even stagnated. However, the number of printed matters in life has not decreased. Every day our lives are full of various printed materials, such as newspapers, magazines, leaflets, product packaging, and so on. The waste and pollution caused by printing technology are usually recessive, and not everyone values it. Unfortunately, people often overlook the waste of resources and environmental pollution caused by the manufacturing process, ink, toner, and printers. The method proposed in this paper uses a color difference model to find a manner that is not easy to notice by the human eye to save ink. The proposed method considers feasibility and practicability, and users can quickly find suitable settings for their applications. Also, through the actual printed pictures, the experimental results show that only 67.57% of the original ink consumption is required to obtain an equivalent print quality that is difficult to perceive by the human eye. Our proposed method will benefit the printing industry and reduce ink consumption on consumer printers, contributing to cost control and being nature-friendly.

INDEX TERMS Image processing, image quality, image color analysis, green products.

I. INTRODUCTION
The printing industry has stepped up its pace in mass manufacturing and printing to meet various daily needs. According to the market report by Smithers Pira, the global printing industry is expected to reach $821 billion by 2022 [1]. Simultaneously, another market forecasting report shows that the printing ink consumption by volume is expected to increase by 9%, from 3.3 million metric tons in 2013 to 3.6 million metric tons in 2023 [2]. Besides, because of the rapid development of digital imaging technology, people have become more sensitive and demanding on the color reproduction and vividness of printed matter. This has prompted the printing industry to progress towards increasing production capacity and developing new printing consumables. However, the rapid growth printing requirements also have a concomitant environmental impact. For example, many Volatile Organic Compounds (VOCs) printing materials are sources of air pollution [3], [4]. More serious and directly related to health problems include the impact of printing consumables on the human body [5], [6]. This research focuses on technologies that provide lower ink and toner consumption and maintain the human eye’s perception to reduce the pollution and waste of resources caused by large-scale printing. In the past, academic literature rarely focused on ink-saving techniques. From the existing approaches, we divide the researched technologies into three categories: printing content classification, halftone method, and color management method. The printing content classification methods classify the information to be printed and adopt different ink configuration strategies to save ink. Many machine learning and neural network-like methods are dedicated to improving classification accuracy [7], [8]. As the classification accuracy is improved, ink management will be more precise.

Halftone methods simulate continuous image tones through dots that vary in size or pitch, resulting in a gradual-like effect [9]–[11]. Reducing the density and size of dots can achieve ink-saving. Therefore, achieving ink-saving with minimal impact on human perception is a topic discussed in this technology. Common methods...
include Amplitude Modulation, Frequency Modulation, and Hybrid Modulation. Amplitude Modulation uses the dotted area’s size to express the shades of the image; Frequency Modulation uses the density of the dots to be arranged to show the level of the image. Hybrid Modulation is a comprehensive application of the characteristics of amplitude modulation and frequency modulation, taking into account the details of the image and the performance of the color. The halftone methods highly depend on the background technology of the printing device. Therefore, these methods are difficult to promote and apply even if their ink-saving effect is good.

Color management approaches focus on studying the correlation between image color and ink and find feasible ways to reduce ink consumption. Our proposed method falls into this category of methods. Some color management methods are classic and still widely used, e.g., under color removal (UCR) [12], [13], gray component replacement (GCR) [14]–[16], under color addition (UCA) [17], and so on. However, these approaches over-rely on expert experience. Even the processes have to be iteratively operated by experts and individually checked by the human eye to ensure output quality. It is inefficient to operate the above process frequently. Because human perception has individual differences, judging the output quality using the human eye is not recommended. Inspired by MacAdam’s research [18], [19] and related researches of color vision Just-Noticeable Difference (JND) [20], we use the color difference model to effectively quantify the required print quality so that users can effectively find the print settings. In this research, our proposed method aims to balance ink-saving performance and visual quality. Simultaneously, we have also increased the convenience of operation. Our proposed method can be applied to process various kinds of input images. By leveraging the characteristics of the CIE (International Commission on Illumination) color difference model, we replace input image color with another imperceptible ink-saving color. By configuring only a few parameters, the user can select the desired printing quality for varying applications. The results show that the proposed ink-saving algorithm can decrease the total ink usage and maintain image quality.

This study uses figures with detailed method descriptions to correctly supplement the previously proposed color scale table generation approach. Moreover, we also introduced the device-dependency of the intensity replacement approach in this research. In other words, this study fully considers the ink-saving strategy of chrominance and luminance domain information. To more intuitively prove the practicality of the proposed method, this study adds experiments in actual printing and measuring ink consumption weight and subjective assessment by human eyes. In the past ink-saving technology literature, few experimental methods used print tests to evaluate ink consumption. However, the advantage of this method is the most direct and convincing way to express the ink-saving effect. The experimental results show that in the case of using only 67.57% of the original ink, the human eye does not see the difference of 92.03% of the printed products. Of the other 7.97% of prints, only 2.59% were considered to be significantly different, and the remaining 5.39% showed little difference in visual effects. This study adds an objective batch printing and weighing experiment. At the same time, subjective evaluation by human eyes is also added to make the proposed method more practical. Besides, when studying the ink-saving theme, we found that there is not much image dataset for evaluating the effect of the algorithm. To this end, we have collected a series of test pictures for future academic research.

II. REVIEW

There are many toner saving approaches have been proposed. In this chapter, we summarize these methods and classify them into conventional methods, color management module-based methods, and halftone-based methods.

A. CONVENTIONAL METHODS

The most popular ink-saving algorithms in printing technology are GCR and UCR. The GCR is proposed by John Yules in 1940 [21], [22]. The concept of this approach is to replace the gray ink that is comprised of cyan, magenta, and yellow inks with black ink. The advantage of GCR is that it enhances the darkness of the image and makes the details more transparent. However, there are some disadvantages to using the algorithm. For example, if more black ink is used, the presence of particle noise will increase and affect the visual smoothness of image quality. Some off-the-shelf software offers varying GCR strength levels for different requirements.

However, this somewhat damages the color saturation in the image and reduces the implementation flexibility. Fig. 1 shows a comparison of the different GCR strength results. Different strength settings make the color and image detail different. The visual result is not ideal when the strength
is the strongest. Fig. 2 shows a more detailed observation image comparison. The darkness of the image has a color shift or discoloration, especially in the shadows of continuous gradients and skin tones.

In addition to GCR, another popular method is UCR [23]. The concept of UCR is to use black ink to reduce the cyan, magenta, and yellow inks used in the dark areas of the image, allowing the dark areas to perform better. Compared to GCR, UCR focuses on ink replacement in dark tones. As a result, UCR retains the overall color saturation and color manipulation flexibility of the image, significantly increasing the continuous tone and skin tone of the GCR in the shadows of bright areas of the image. However, since the UCR operates in a dark tone, it is more difficult to control the color change of the image in the dark tone region. Generally, GCR’s color ink saving performance is superior to UCR. The commonality between GCR and UCR is that for nonprofessionals, the print results after any operation are not easy to evaluate.

Looking at the limitations of the above conventional methods, in recent years, many printing ink-saving methods and patents based on different thinking have also been proposed. We classify these methods, analyze them from the architectural and principle aspects of the printing, and create a flow chart that can be improved by the printing process. The state-of-the-art printing framework is shown in Fig. 3.

According to the state-of-the-art printing framework, these approaches can be classified into two major processing strategies: Color Management Module (CMM) strategy and halftone strategy. And, the image reproduction process comprises three-stage processes. In the first stage, the input images or data contents are classified to benefit further toner-saving processes. Next, a proper ICC (International Color Consortium) profile is applied to convert the input contents from device-dependent color space to another device-independent color space. Various image processing algorithms can be adopted to preserve the preferable color properties in this device-independent color management module stage. After finishing the second stage, the color is converted into CMYK (Cyan, Magenta, Yellow, and Black) using a specific ICC profile (e.g., Specifications for Web Offset Publications, General Requirements for Applications in Commercial Offset Lithography, and so on). Different sizes, densities, and forms of the toners (or inks) for each pixel are decided in the third stage.

Generally, the printing system’s pre-processing stage will classify digital content into several types, such as pictures, text, graphics, monochrome, and multicolor. Fig. 4 shows the concept of printing content classification. An excellent content classification can be leveraged to speed up the printing process and decrease total toner usage. For example, if printing content is mainly composed of texts and graphics, which are mostly formed by monochromatic arcs, the concentration of toner or ink can be controlled to achieve toner-saving with the acceptable printing quality. In 2016, B. Montrucchio et al. proposed a quasi-random sequence-based approach to reduce the number of dots in monochromatic printing as a positive example [24]. Moreover, there are many approaches proposed to reduce toner usage. These approaches can be separated into two types: Color Management Module-based methods and halftone-based methods.

### B. Color Management Module-Based Methods

Many digital images are not monochrome. In printing process, color images will be converted from RGB color space to device-invariant CIEXYZ color space for advance operation. Some classic toner-saving algorithms (e.g., the Gray Component Replacement approach, the Under Color Removal approach, and the Under Color Addition approach) can be applied while converting these color images to specific hardware-dependent CMYK color space. These toner-saving approaches have widely been adopted in some commercial software, for example: Adobe Photoshop. However, it is difficult either to select proper parameters for above approaches or to iteratively change the parameters for each image. If the parameters are improper, many side effects will show, for example: color bias, low concentration, and so on.

Various CMM-based methods have been proposed to provide more toner-saving solutions. C. H. Son et al. proposed a method to reduce colorant usage by limiting the total-colorant quantity and dot-visibility [25] in 2010. The total colorant usage can be reduced by correlating the CIELAB image color with CMYKLcLm colorants. In 2012, L. Shapira and B. Oicherman proposed a dynamic color transformation approach to reduce ink usage [26]. Combining the weighted entropy filter with skin preserving design, authors replace the image CMYK value with increased black by referencing the determined Region Of Interest (ROI) of the input image.

### C. Halftone-Based Methods

The halftone-based toner-saving strategy is mainly applied to the hardware device of printing facilities. Therefore, halftone-based approaches can be used to collaborate with CMM-based methods. Many halftone-based methods are proposed to process text-based content [27]–[29], and image-based content. For image-based applications, the halftone-based methods can be classified into three types: Amplitude Modulation (AM) [30], Frequency Modulation (FM) [31], and Hybrid Modulation [32]. By modifying dot size of toner for each pixel, the amplitude modulation can control concentration of printed image. In the frequency modulation, each dot size of ink is fixed. Concentration
of printed image is controlled by the dot density for each pixel. Hybrid modulation is composed of the characteristic of above amplitude modulation and frequency modulation. Amplitude modulation is widely used in various printed products, laser printing, photocopying, and so on; frequency modulation is applied to inkjet printing or large-format printing; hybrid modulation is rare unless the high printing quality is needed. Many approaches are inspired by above three types of halftone-based methods. In 2021, R. Isumi et al. proposed a decolorization method for business/presentation graphics [33]. A good ink-saving effect can be obtained after converting the image content through short line segments, zigzag lines, and wave lines. However, the method proposed by R. Isumi et al. is different from the application scope of this research. This research aims to reduce the usage rate of ink or toner in printing based on the perception of the human eye.

III. THE PROPOSED METHOD

Our proposed toner saving approach is introduced in this chapter. In Section III-A, the overview of our system is given. Section III-B presents the offline color scale table generation process. This offline process is designed to improve the application performance of our proposed method. The online similar color replacement is introduced in Sections III-C. Section III-D presents the device-dependent intensity replacement method that can significantly reduce the amount of ink used.

A. SYSTEM FRAMEWORK

System flowchart of our proposed method is shown in Fig. 5. This approach is designed as two main processes: offline process and online process. The offline process is used to prepare the prerequisite color scale table for online process to increase the execution performance. In application, parameters for the offline process will only need to be
assigned at the first time. To satisfy various application, user can modify the above parameters dynamically. Next, the online process is applied to process the input image to decrease the toner usage afterward. In Sections III-B to III-D, the procedure of each submodule in our proposed approach will be described in detail. Besides, many figures will be given to illustrate the processing effect.

### B. COLOR SCALE TABLE GENERATION

Generally, trade-off between toner usage and printing quality would be the main problem in toner saving topics. Besides, the complexity of the algorithm controlled to satisfy real-time printing requirement is also very important. In this section, we will first introduce an offline look-up table generation method. This method can improve the execution efficiency of the color replacement that will be introduced in Section III-C.

In color science, there are many methods used to measure the distance between any two colors. The International Commission on Illumination (CIE) defines several color difference calculation methods. The CIE94 [34]–[37] used in this research is one of the color difference calculation methods. The color difference formula design defined by the CIE is mainly based on the CIELAB color space. Unlike the RGB color space broadly used in digital image processing, CIELAB is designed to consider the human eye’s differences in the perception of different colors. \( L^* \) in the CIELAB color space represents perceived brightness, and \( a^* \) and \( b^* \) represent four unique colors of human vision: red, green, blue, and yellow. Although there are differences in the perception of individual human eyes, the human eye has a lower discrimination ability for any two different colors with a smaller color difference than any two different colors with a larger color difference. Based on the CIE94 color difference formula, three characteristics can be found when we assume \( \Delta E_{94}^* = 1.0 \), referring to the ellipse in Fig. 6 [19], [20]. First of all, this color difference model is an isotropic distribution model. This feature is conducive to establishing a low-complexity model to achieve the ink-saving algorithm, and this is the starting point for this research to choose this color model. Second, the farther away from the circle’s center \((a^*, b^*) = (0, 0)\), the larger the ellipse. This feature shows that when designing this color difference model, the CIE has taken into account the human eye characteristics that have low discrimination for any two different high-saturation colors with similar or identical hues. Third, the short axis of the ellipse indicates that the human eye’s perception of the difference in hue changes is stronger than the perception of color saturation changes. In the CIE94 color difference formula, the larger the value of \( \Delta E_{94}^* \), the greater the difference between any two colors. In addition, the amount of color difference that human vision can detect will also vary with physiological differences, such as age, gender, cognition, and so on.

Therefore, by leverage the uniformity attribute of the CIE94 color difference formula and the color-tolerance ellipse figures in Fig. 6, we generate color scale table to represent the similar color in CIELAB color space.
Assume that, reference color is shown as follows. FIGURE 6.

The weighting factors \( k_L, k_1, \) and \( k_2 \) are set to 1, 0.045, and 0.015 respectively [20]. The \( k_C \) and \( k_H \) are set to 1.

Fig. 6 is generated by using CIE94, whose formula is shown as follows:

\[
\Delta E_{94}^* = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C_{ab}^*}{k_C S_C}\right)^2 + \left(\frac{\Delta H_{ab}^*}{k_H S_H}\right)^2}.
\]  

(1)

Assume that, reference color is \((L^*_r, a^*_r, b^*_r)\) and another color is \((L^*_l, a^*_l, b^*_l)\), where,

\[
\begin{align*}
\Delta L^* &= L^*_r - L^*_l \\
\Delta H_{ab}^* &= \sqrt{\Delta a^{*2} + \Delta b^{*2} - \Delta C_{ab}^{*2}} \\
\Delta C_{ab}^* &= \sqrt{a^{*2}_r + b^{*2}_r - a^{*2}_l - b^{*2}_l} \\
\Delta a^* &= a^*_r - a^*_l \\
\Delta b^* &= b^*_r - b^*_l \\
S_L &= 1 \\
S_C &= 1 + K_1 \sqrt{a^{*2}_l + b^{*2}_l} \\
S_H &= 1 + K_2 \sqrt{a^{*2}_l + b^{*2}_l}
\end{align*}
\]

The weighting factors \( k_L, K_1, \) and \( K_2 \) are set to 1, 0.045, and 0.015 respectively [20]. The \( k_C \) and \( k_H \) are set to 1.

While the center coordinate of ellipsoid and \( \Delta E_{94}^* \) in (1) are given, the corresponding coordinates which satisfy the CIE94 formulas can be derived. Considering the human perception is more sensitive to brightness variation than color variation [38], we only use those coordinates that fulfill \( \Delta L^* = 0 \) in above (1) while given specific reference coordinate. In other words, we will only operate the color information in \( a^*-b^* \) plane (chrominance domain) instead of \( L^*-a^*-b^* \) space (luminance and chrominance domain) in color scale table generation stage. Thus, (1) can be simplified as follows:

\[
\Delta E_{94}^* = \sqrt{\left(\frac{\Delta C_{ab}^*}{S_C}\right)^2 + \left(\frac{\Delta H_{ab}^*}{S_H}\right)^2}.
\]  

(2)

Moreover, the distribution of ellipses have isotropic characteristic can be observed from the Fig. 6 or derived from the CIE94 formulas. Assume without loss of generality that \( b^*_r \) and \( b^*_l \) equal 0. The CIE94 color difference formulas in (1) can be simplified as follows:

\[
\begin{align*}
\Delta H_{ab}^* &= \sqrt{\Delta a^{*2} - \Delta C_{ab}^{*2}} \\
\Delta C_{ab}^* &= \sqrt{a^{*2}_r - a^{*2}_l} \\
\Delta b^* &= 0 \\
S_C &= 1 + 0.045 \sqrt{a^{*2}_l} \\
S_H &= 1 + 0.015 \sqrt{a^{*2}_l}
\end{align*}
\]

If \( a^*_r \) and \( \Delta E_{94}^* \) are given, then \( a^*_l \) can be derived by solving following quadratic equation.

\[
\begin{align*}
\Delta E_{94}^* &= \frac{(a^*_r - a^*_l)^2}{(1 + 0.045 a^*_l)^2} \\
2 a^*_l &= \sqrt{4 a^*_r^2 - 4 (a^*_r^2 - \Delta E_{94}^*^2 (1 + 0.045 a^*_r)^2)} \\
\frac{2 a^*_l}{2} &= \frac{2 a^*_r}{2} - \Delta E_{94}^* (1 + 0.045 a^*_r)
\end{align*}
\]  

(3)

In this section, (4) is applied to generate color scale table. From Fig. 7(a) to 7(e), we illustrate concept of the color scale table generation approach. First of all, an acceptable color difference \( \Delta E_{94}^* \) is assigned. In the following instance, we use \( \Delta E_{94}^* = 2 \). The color difference \( \Delta E_{94}^* \) is correlated with just noticeable difference. Hence, if \( \Delta E_{94}^* \) of two colors is large, it means that human can easily distinguish these two colors. Although a larger \( \Delta E_{94}^* \) can be used to significantly reduce the amount of toner used, we still recommend that users choose an appropriate value according to the application. Then, the maximum absolute chromatic value is selected for the initial value \( a_1 \). In the following description, \( a_1 = 107.8596 \) is applied, because when the color space is sRGB and the reference white point is D65, the ranges of \( a_1 \) and \( b_1 \) are \(-86.1758 \) to \( 98.2467 \) and \(-107.8596 \) to \( 94.4846 \), respectively. If we substitute \( a^*_1 = 107.8596 \) and \( \Delta E_{94}^* = 2 \) into (4), then, \( a^*_2 = 119.5670 \) and \( 96.1522 \) can be derived. Comparison with the solutions \( a^*_2 \) and Fig. 7(a), 119.5670 and 96.1522 is assigned to \( a_0 \) and \( a_2 \) respectively.

Next, let \( a^*_2 = a_2 = 96.1522 \), we substitute \( a^*_2 \) and \( \Delta E_{94}^* = 2 \) into (4), then, \( a^*_3 = 86.3782 \) and 105.9263 can be derived. Comparison with the solutions \( a^*_3 \) and Fig. 7(b), 86.3782 and 105.9263 are assigned to \( a_3 \) and \( t_1 \) respectively.

Again, let \( a^*_3 = a_3 = 86.3782 \), we substitute \( a^*_3 \) and \( \Delta E_{94}^* = 2 \) into (4), then, \( a^*_4 = 76.6042 \) and 96.1522 can be derived. Comparison with the solutions \( a^*_4 \) and Fig. 7(c), 76.6042 and 96.1522 are assigned to \( a_4 \) and \( a_2 \) respectively.
Fig. 7(d) is the diagram after 5\textsuperscript{th} step operation. The concept of the color scale table generation becomes more concrete.

The algorithm for scale table generation is completed by repeating the above procedures until the left-side vertex of generated ellipse close to or equal to 0. Many ellipses along a*-axis can be generated in the process. From Fig. 7(a) to 7(d), the dashed ellipses are applied to assist to generate continuous solid ellipses. The vertices and centers of solid ellipses are left and became the elements of color scale table \( T \). By observing Fig. 7(e), the generated ellipses are continuous along every major axis from one ellipse to another ellipse. The color scale table \( T \) can be denoted as follows:

\[
T = \{a_i \geq 0 \mid i \geq 0, i \in \mathbb{Z} \} \neq \emptyset
\]

In above instance, the final color scale table \( T \) is \{0, 3.4079, 5.7146, 8.4776, 11.2406, 14.5501, 17.8596, 21.8237, 25.7879, 30.5361, 35.2844, 40.9718, 46.6593, 53.4717, 60.2842, 68.4442, 76.6042, 86.3782, 96.1522, 107.8596, 119.5662\}. 

**FIGURE 7.** The series of diagrams illustrate the concept of the color scale table generation method. The schematic diagrams (a) to (d) are the operation results of steps 1, 2, 3, and 5. Diagram (e) means the color scale table is generated using the sequence of vertices and centers of solid ellipses.
119.5670). The color scale table will be applied to process color replacement in Section III-C.

Furthermore, the corresponding degree table is generated by using the minor axes for each ellipse simultaneously. Due to the center coordinate and vertices of each ellipse are given, the co-vertices of each ellipse can be derived by using (2). In Fig. 8, \((a_1, b_1)\) and \((a_1, -b_1)\) are the derived co-vertices of ellipse 1. \(L_u\) means the line segment connecting origin of coordinate to \((a_1, b_1)\); \(L_d\) means the line segment connecting origin of coordinate to \((a_1, -b_1)\). The degree of interest for ellipse 1 is the included angle between sides \(L_u\) and \(L_d\). This degree \(\phi_1\) can be derived by:

\[
\phi_1 = 2 \tan^{-1} \left( \frac{b_1}{a_1} \right)
\]

The remaining degrees for each corresponding ellipse can be done in the same manner.

Because this degree is related to above color scale, the color-scale-dependent degree table \(D\) can be denoted as follows:

\[
D = \{\phi_i \mid a_{2i} \leq t < a_{2i-2}, t \in T, i \geq 1, i \in \mathbb{Z}\} \neq \emptyset
\]

The advantage of this model is that after integrating the JND and CIE94 color difference models, users can modify the required color difference value according to different needs, and the proposed method can directly generate the corresponding color scale table without the need for users to fine-tune. In response to the need for different color accuracy, this design is very intuitive and convenient. It is important to note that the proposed method will reduce the ink-saving effect if the required color difference value is reduced. On the contrary, if the required color difference value acceptable to the user is large, the color scale table generated by the proposed method will produce a better ink-saving effect.

C. SIMILAR COLOR REPLACEMENT

In this section, the offline-generated color scale table is used to replace the CIE L\(^*\)a\(^*\)b\(^*\) color information of given image to decrease toner usage. Due to the luminance information is predominant in color image, the L\(^*\)-term in CIE L\(^*\)a\(^*\)b\(^*\) color space is preserved in our proposed similar color replacement. First of all, we transfer \((a^*, b^*)\) chrominance value in Cartesian coordinate system to polar coordinate \((\rho, \phi)\). The relation between Cartesian coordinate and polar coordinate can be shown as follows:

\[
\rho = \sqrt{a^*{}^2 + b^*{}^2}, \\
\phi = \tan^{-1} \left( \frac{b^*}{a^*} \right)
\]

where, \(\rho\) means the radial coordinate, and \(\phi\) means the angular coordinate.

The interior meaning of the radial coordinate is the saturation of color. If the radius of a specific color is large, it means the saturation of color is high. In other words, the color saturation is low while the radial coordinate is close to origin of coordinate. Besides, the angular coordinate means color hue. In (2), the direction of major axis in specific ellipse is equal to the direction of the corresponding radial coordinate. Moreover, the direction of minor axis in specific ellipse is approximately to the direction of the corresponding angular coordinate. By observing the \(a^*-b^*\) plane of the CIE94 shows in Fig. 6, the saturation variation along radial coordinate direction is more difficult to differentiate than the hue variation along angular coordinate direction. Our proposed color replacement approach is mainly applied to radial coordinate to remap each saturation value of input image. In Section III-B, the color scale table generation is introduced. Assume the generated color scale table is \(T = \{t_1, t_2, \ldots, t_n\}\); \(D = \{d_1, d_2, \ldots, d_n\}\) is the corresponding degree table; an input color and processed color is \((a^*, b^*)\) and \((a_d, b_d)\) respectively. The pseudocode of similar color replacement can refer to Algorithm 1. In the pseudocode, the purpose of lines 6 to 12 is to select a proper radial coordinate from the color scale table and get the corresponding degree information. The goal from line 13 to line 20 is to downsample the degree information. The aim from line 21 to line 33 is based on different quadrants; the proposed method will convert the above-mentioned radial coordinate and degree information into toner-saving color.

Based on the generated color scale table, the image color is grouped. Furthermore, if the selected \(\Delta E_{94}^*\) in (3) is small, the color density of the color replacement result will be relatively high. Generally, trade-off between color density and perceptual tolerance is required. The low color density of \(\Delta E_{94}^*\) is preferred to decrease toner usage.

According to printing quality requirement, the parameters of color scale table generation in offline processing can be modified optionally. While \(\Delta E_{94}^*\) is set to 1.2, 2.4, and 3.6 respectively, the processed images and the corresponding color densities is shown in Fig. 9.

By observing Fig. 9, our proposed similar color replacement approach can be used to moderately reduce image saturation based on the characteristic of human perception.

D. INTENSITY REPLACEMENT

In this section, we propose a device-dependent method that can significantly reduce the amount of ink used. In the case of CMYK four-color separation printing, our proposed method can appropriately reduce the color saturation to decrease the amount of color ink usage. However, the darker image content in the image will also consume more black ink, and even use the color ink mixing method to achieve the dark printing needs. Therefore, we add a device-dependent intensity replacement design. This design allows the user to more flexibly evaluate the influence based on image quality and ink-saving performance, select the image quality that he wants, and achieve significant ink-saving effects. The larger the brightness value of the image, the less ink is printed. In this research, gamma look-up table and slope look-up table approach are proposed to process the intensity replacement.
FIGURE 8. The degree of interest for Ellipse 1 is the included angle between $L_u$ and $L_d$.

Algorithm 1: Algorithm for Similar Color Replacement

**Input:** color information ($a^*$, $b^*$) from original image

**Output:** processed toner-saving result ($a_d$, $b_d$)

1: $R_s = 0$
2: $S_d = 0$
3: $D_s = 0$
4: $\rho = \sqrt{(a^*^2 + b^*^2)}$
5: $\phi = \arctan(b^*, a^*)$
6: for $i = 2$ to $n$ do
7:  if $\rho \geq t_{i-1}$ and $\rho < t_i$ then
8:      $R_s = t_{i-1}$
9:      $S_d = d_{i-1}$
10:     break
11:  end if
12: end for
13: for $j = 1$ to $360/S_d$ do
14:  $\phi_{\min} = S_d \times (j - 1)$
15:  $\phi_{\max} = S_d \times j$
16:  if $(\phi + S_d/2) > \phi_{\min}$ and $(\phi + S_d/2) \leq \phi_{\max}$ then
17:     $D_s = (\phi_{\min} + \phi_{\max} - S_d) / 2$
18:     break
19: end if
20: end for
21: if $D_s \geq 0$ and $D_s < 90$ then
22:  $a_d = R_s \times \cos(D_s \times \pi/180)$
23:  $b_d = R_s \times \sin(D_s \times \pi/180)$
24: else if $D_s \geq 90$ and $D_s < 180$ then
25:  $a_d = -R_s \times \sin((D_s - 90) \times \pi/180)$
26:  $b_d = R_s \times \cos((D_s - 90) \times \pi/180)$
27: else if $D_s \geq 180$ and $D_s < 270$ then
28:  $a_d = -R_s \times \cos((D_s - 180) \times \pi/180)$
29:  $b_d = -R_s \times \sin((D_s - 180) \times \pi/180)$
30: else
31:  $a_d = R_s \times \sin((D_s - 270) \times \pi/180)$
32:  $b_d = -R_s \times \cos((D_s - 270) \times \pi/180)$
33: end if

Gamma look-up table is broadly used in display and digital image processing field. We use the gamma look-up table approach to transform image intensity information. Assuming that the value range of the input $V_{in}$ is between 0 and 255, and the value range of the output $V_{out}$ is also between 0 and 255, the gamma operation formula is as follows:

$$V_{out} = 255 \left( \frac{V_{in}}{255} \right)^{\gamma}$$

Different $\gamma$ values will change the relationship between input and output, and the relationship is shown in Fig. 10. After the user prints out Fig. 11 shown below, they can decide which gamma to use to process the input image’s brightness to achieve intensity replacement. However, by observing the image printing effect using the gamma look-up table, we found that the visual effect of this output result for printing is not ideal. The intensity
value of the input image!drastically increases in the darker areas, and the noise and detail are too abrupt. At the same time, the image contrast is reduced after the high-intensity input information is processed, resulting in a more unpleasant printing effect.

To make the tone of the brightness change more slowly and at the same time have a significant ink-saving effect, we propose another way to change the brightness of the image input and output by changing the slope. Assume that the value range of the input $V_{in}$ is between 0 and 255, and the value range of the output $V_{out}$ is also between 0 and 255. Corresponding to the different slopes $\alpha$, the relationship of the slope modification operation is as follows:

$$V_{out} = \alpha V_{in} + 255(1 - \alpha)$$

The smaller the value of the slope $\alpha$, the higher the ink savings, especially in dark tones. Fig. 12 shows the slopes of 1.00, 0.95, 0.90, 0.85 and 0.80.

With the different characteristics of each printing device and the different user requirements, the recommended operation is to let the users output the design of the following Fig. 13 with their printer, and then decide which slope to use to process the brightness of the input image. It is recommended to provide the user with more slope scale options to observe the performance of the printer output at different slopes. In the experiment, we use the Hewlett-Packard Office Jet 8210 for image ink saving testing. The slopes we chose to print this inkjet printer are: 1.00, 0.98, 0.96, 0.94, 0.92, 0.90, and 0.80, in Fig. 13.

According to the printed effect, we choose to use the slope modification look-up table with a slope of 0.94 for the basis of image intensity conversion. In the experimental results, we use both subjective and objective methods to present the effects of intensity replacement.

IV. EXPERIMENTAL RESULT

Our proposed method and its effects are separately explored in the experiments. First, the effect based on human perception and color difference model is discussed. From this part of the experiment, the result shows that our proposed method can significantly reduce the total number of image colors in a state where the human eye can hardly perceive it. The experimental results show that the image color saturation
The purpose of reducing the total number of image colors and reducing the color saturation is to reduce ink rendering and the amount of ink used in solid colors. Besides, to be closer to the user’s operational habits and to verify the reliability of our proposed method, we have taken many additional photographs for further analysis. There are 464 photographs in total, which are very diverse and are classified into life, nature, night scenes, architecture, and streetscapes. These photographs are used for objective and subjective experimental data evaluation. Among them, the objective part uses HP Office Jet 8210 for printing to confirm the effect of ink saving. In the subjective part, multiple observers evaluate the HP Office Jet 8210 printout results under standard lighting condition of the X-Rite Macbeth light booth. In Section IV-A, the experiment demonstrates that our proposed method can reduce the total color usage and appropriate saturation reduction while maintaining image quality. The intensity replacement approach has not been applied in this part of the experiment. The experimental results are presented using a computer monitor and will have a better effect. In Section IV-B, the results are directly output using the HP Office Jet 8210 printer, so the intensity replacement approach proposed in Section III-D is applied at this time.

A. OBSERVATION COLOR AND SATURATION

Our proposed approach is evaluated with two standard color image datasets, the Kodak dataset and the IMAX dataset [39]. Fig. 14(a) shows 24 images of the Kodak dataset. The 18 images of IMAX dataset are shown in Fig. 14(b). The Kodak dataset is a standard dataset and is widely used in various color image processing researches. This dataset contains 24 full-color $768 \times 512$ images. The features of the Kodak dataset include very high spectral correlation, smoother color gradient, and low saturation. The IMAX dataset is also called the McMaster dataset. This dataset was created when McMaster University and industrial partners developed a new color demosaicing method. The IMAX dataset is digitized after shooting with Kodak film. The dataset has 8 high-resolution color images with a resolution of $2310 \times 1814$. In this research, we use X. Li et al. [39] cropped 18 $500 \times 500$ images for experiments. According to X. Li’s analysis, the image spectral correlation of the IMAX dataset is low. The color gradient is higher than the Kodak dataset, and the color saturation is much higher than the Kodak dataset. These two datasets with different characteristics are used for experiments to illustrate the flexibility of our proposed method. To demonstrate the visual effect, many color difference settings of CIE94 are adopted to generate its corresponding color scale table. Compared with our previous works [40], we leverage the saturation of whole image to achieve toner usage. The processed image is more natural than our previous works. To demonstrate the improvement, we accumulate the color histogram of processed image to objectively assess the toner usage and image quality. Besides, the total saturation is...
accumulated to determine the performance of toner saving. The color of each pixel of an image is represented by (R, G, B), where the range of R, G, B is between [0, 255]. The color usage in this research represents how many different (R, G, B) are used in the image. The average color usage comparison table is shown in Tables 1. The results show that our proposed method can be used to group the similar color. The above advantage can be used to operate color remapping to reduce toner usage in the stage of color management printing process. The result shows that our proposed method can remarkably reduce the total color usage.

The average saturation comparison list for the Kodak dataset and IMAX dataset is shown in Tables 2. The value range of saturation is between [0, 1]. The smaller the value, the lower the saturation. Conversely, the larger the value, the higher the saturation. The result shows that our proposed method can moderately reduce the average image saturation. Leveraging the characteristics of color difference model and human perception, our proposed method modifies each pixel color to local low-saturation color by using color replacement processing.

The respective visual comparison results of our proposed approach is shown in Fig 15.

**B. OBJECTIVE AND SUBJECTIVE COMPARISONS**

In this section, we use HP Office Jet 8210 to directly print the images to more specifically present our proposed ink-saving effect based on human perception and color difference model. The printer’s ink cartridges design is identical to many printing devices and is separated by four CMYK colors. The most ink-intensive process when printing is to output various color images. For this reason, we take 464 photographs and printed images on the HP Office Jet 8210 inkjet printer for objective ink-saving evaluation and subjective human eye evaluation. To further study the ink-saving algorithm research, we also provide these 464 images for academic research. We divide these images into five categories: life, nature, night scenes, architecture, and streetscapes. Part of the thumbnails of these images is shown in Fig. 16.

1) OBJECTIVE ASSESSMENT

All computer peripherals have their characteristics, such as screens, printers, and so on. When they output images, they produce different results due to their different characteristics. Therefore, color management through a separate ICC profile is the current practice. We will follow this approach when we conduct an objective assessment. First, when using Matlab for this experiment, we announce that the ICC profiles for all image files are sRGB, and the output ICC profiles are simulated by General Requirements for Applications in Commercial Offset Lithography 2013 (GRACol 2013) and Specifications for Web Offset Publications 2013 (SWOP 2013), respectively. Calculate the amount of CMYK ink used before and after the proposed ink-saving algorithm for each image. After converting five types of images using GRACol 2013 and SWOP 2013, the total ink usage simulation is performed. Each simulation result is normalized by its CMYK maximum value. Fig. 17 and 18 show the simulation results. The $E^*_{94}$ and intensity replacement slope value $\alpha$ are set to 2.4 and 0.94, respectively.

In the actual printing and ink consumption test, the ambient relative humidity is controlled between 62 ± 2%, and the temperature is controlled at 21 ± 1°C. The operation process
TABLE 1. Average color usage of each approach (or different $\Delta E_{94}^*$ settings) after processing the Kodak dataset and the IMAX dataset.

| Dataset | Original | AprxK [40] | Proposed $\Delta E_{94}^* = 0.6$ | Proposed $\Delta E_{94}^* = 1.0$ | Proposed $\Delta E_{94}^* = 1.4$ | Proposed $\Delta E_{94}^* = 1.8$ | Proposed $\Delta E_{94}^* = 2.2$ | Proposed $\Delta E_{94}^* = 2.6$ |
|---------|----------|------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Kodak   | 35613    | 25372      | 32946                         | 26873                         | 21926                         | 17826                         | 14698                         | 13386                         |
| IMAX    | 115399   | 99090      | 64808                         | 45051                         | 33967                         | 26587                         | 20995                         | 18758                         |

TABLE 2. Average saturation comparison while applying different approaches (or different $\Delta E_{94}^*$ settings).

| Dataset | Original | AprxK [40] | Proposed $\Delta E_{94}^* = 0.6$ | Proposed $\Delta E_{94}^* = 1.0$ | Proposed $\Delta E_{94}^* = 1.4$ | Proposed $\Delta E_{94}^* = 1.8$ | Proposed $\Delta E_{94}^* = 2.2$ | Proposed $\Delta E_{94}^* = 2.6$ |
|---------|----------|------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Kodak   | 0.3080   | 0.2485     | 0.2989                        | 0.2926                        | 0.2856                        | 0.2766                        | 0.2715                        | 0.2669                        |
| IMAX    | 0.5480   | 0.5297     | 0.5264                        | 0.5159                         | 0.5037                         | 0.4745                         | 0.4707                         | 0.4802                        |

is equipped with cotton gloves to reduce skin moisture and salt effects. The paper used for image output is the Double A 80 grams per square meter (gsm) A4 size. Each test pattern uses full-board A4 single-sided printing. In addition, the weighing of the ink usage is based on the average of three measurements, and the operation steps are:

1) CMYK ink cartridges are weighed and recorded separately.
2) Load the CMYK ink cartridges into the printer to print the classified image.
3) Remove the CMYK ink cartridges for individual weighing and record.
4) Calculate the different weights before and after the ink is used in Steps 1 and 3.

The difference in weight before and after ink use is recorded as follows. Table 3 records the inks required to print the entire set of images without using the ink-saving algorithm. For example, it needs to use 0.6-gram cyan ink, 3.1-gram magenta ink, 4.6-gram yellow ink, and 3.6-gram black ink to print a complete set of pictures of Life.

Table 4 records the inks required to print the entire set of images using our ink-saving algorithm. Based on the results of Tables 3 and 4, the cumulative CMYK weights to print the entire datasets show the actual ink savings in the case of large scale printing. Table 5 shows the results, in which the ink-saving rate $\xi$ is calculated in the following formula:

$$\xi = \left( \vartheta_o - \vartheta_p \right) / \vartheta_o \times 100$$

where, $\vartheta_o$ means the original ink consumption weight, and $\vartheta_p$ means the proposed method ink consumption weight.

From the actual data, it seems that when the test uses $\Delta E_{94}^* = 2.4$, and the intensity replacement slope $\alpha$ is set to 0.94, the ink usage only needs about 67.57% of the original printing. In a large number of printing applications, it can achieve a considerable ink-saving effect, thereby achieving the effect of saving resources and environmental protection. The amount of ink after the actual output from the printer is compared with the simulation results of the previous GRACoL2013 and SWOP2013. The values are not consistent. The reason depends on factors such as the printer’s own ICC profile, printer software, and image processing algorithms on the hardware.

2) SUBJECTIVE ASSESSMENT

The subjective assessment is carried out by visual observation. We randomly selected 34 volunteers and 10 other subjects who are currently engaged in image quality occupations. According to the study of I. Abramov et al. [41], the color vision has gender differences. To confirm that the proposed method is universally applicable, the gender ratio of our participants is 1:1. According to the research results shared by Munsell Color Science Laboratory of Rochester Institute of Technology [42], age can also cause differences in color discrimination ability. The participants we selected are not over 50 years old. The test method randomly selects two pictures of the same content for each group from the pictures printed by the ink-saving algorithm and the no-use ink-saving algorithm. Each participant in the process observed a total of 10 pairs of images. Among the participants mentioned above, two male and two female observers with experience in image processing individually observed six additional pairs of images to ensure that the printing effects of all 464 images were whole evaluated. The selected pictures are no longer placed back. Because the Life group has only 44 datasets, the insufficient part is supplemented by the Nature dataset. Before the test, we tell the participant that the observed images may be the same and may be different. The intention is to reduce the participant’s preconceived idea so that the test result is more objective. During the process, the participant sits in front of the light booth, and we switch the color temperature of the light source according to the participant’s request. The used light booth is the X-Rite Macbeth SpectraLight III, and the color temperature that can be switched includes A, Horizon, TL84, CWF, and D65. Using a light booth as the viewing environment is because the light booth can provide many familiar different light sources. These different spectra provide a more objective test environment for differences in visual adaptation and
preferences between people. One of the participants in the process of image comparison is shown in Fig. 19.

In the process of participants observing images, we will ask participants the following questions:
FIGURE 18. The average ink consumption of the five categories was compared based on SWOP 2013. Blue bars mean the performance without the ink-saving algorithm, and orange bars indicate the performance with our ink-saving algorithm. ($\Delta E^*_{94} = 2.4, \alpha = 0.94$)
TABLE 3. This table records the amount of individual ink required to print different datasets without using our ink-saving algorithm. The unit is gram. ($\Delta E_{94}^{*} = 2.4, \alpha = 0.94$).

| Categories | Life | Nature | Night Scene | Architecture | Streetscape |
|------------|------|--------|-------------|--------------|-------------|
| Cyan       | 0.6  | 5.0    | 3.8         | 2.9          | 3.6         |
| Magenta    | 3.1  | 5.1    | 5.1         | 4.1          | 5.0         |
| Yellow     | 4.6  | 10.5   | 5.0         | 5.4          | 7.8         |
| Black      | 3.6  | 10.6   | 11.5        | 10.9         | 13.0        |
| Average    | 2.975| 7.800  | 6.350       | 5.825        | 7.350       |

TABLE 4. Amount of individual ink required to print different datasets using our ink-saving algorithm. The unit is gram. ($\Delta E_{94}^{*} = 2.4, \alpha = 0.94$).

| Categories | Life | Nature | Night Scene | Architecture | Streetscape |
|------------|------|--------|-------------|--------------|-------------|
| Cyan       | 0.3  | 3.6    | 2.7         | 1.7          | 2.7         |
| Magenta    | 2.2  | 3.9    | 4.0         | 2.4          | 3.8         |
| Yellow     | 3.7  | 7.9    | 4.0         | 3.0          | 6.1         |
| Black      | 1.7  | 6.8    | 7.7         | 5.3          | 8.4         |
| Average    | 1.975| 5.550  | 4.600       | 3.100        | 5.250       |

TABLE 5. Amount of ink used for each color after printing all the images, as well as the ink saving effect. ($\Delta E_{94}^{*} = 2.4, \alpha = 0.94$).

| Ink cartridge | Total Cyan | Total Magenta | Total Yellow | Total Black |
|---------------|------------|---------------|--------------|-------------|
| Original      | 15.9 g     | 22.4 g        | 33.3 g       | 49.6 g      |
| Proposed method | 11.0 g     | 16.3 g        | 24.7 g       | 29.9 g      |
| Ink-saving rate | 30.82%    | 27.23%        | 25.83%       | 39.72%      |

FIGURE 19. One of the participants is using the D65 color temperature to compare the difference between the two images.

Question 1: Do you think the two images currently being observed are the same? (Also, participants can request to switch the color temperature of the light booth at any time to reconfirm until they can answer the question.)

- If the participant thinks the two images are the same, then we will let the participants observe the next pair of images.
- If the participant thinks that the two images are different, we will ask the next question.

Question 2: Based on question 1, if you think that the two images are different, do you think the difference between the two images is significant?

- Record the evaluation given by the user for subsequent statistics.

After the results are aggregated, the following discussion is conducted. The statistical table is shown in Table 6. First, if the participant does not see the difference in the test image, that means our proposed ink-saving algorithm retains the effect that is closely related to the visual perception of the original image. With a total of 464 votes, this type of image accounted for 427 votes. In other words, about 92.03% of the images did not show the side effect on the processed images. Further explore 7.97% of the images that can be distinguished, of which 67.57% consider that the images are not much different.

The participants who looked at the differences in images and thought that the differences are significant are because they found image tone changes. Exploring the reason, this is because the intensity replacement in our proposed algorithm significantly reduces the amount of ink used. Moreover, the human eye is more sensitive to changes in brightness than color. If the print is intended to approximate the performance of the original image, we recommend appropriately adjusting the slope value for intensity replacement.

According to the data, we have collected, all subjects who can observe image differences are engaged in work related to image quality. However, not everyone who works on image quality has noticed the difference in images. Looking back at the subjective experiments of the human eye, we did not
TABLE 6. The summary of subjective opinion statistics. The unit in this table is the number of votes.

| Dataset        | Can’t see the difference | Can see the difference |
|----------------|--------------------------|------------------------|
|                |                          | (small difference, obvious difference) |
| Life           | 40                       | 4 (3, 1)               |
| Nature         | 120                      | 9 (5, 4)               |
| Night Scene    | 73                       | 11 (7, 4)              |
| Architecture   | 75                       | 6 (5, 1)               |
| Streetscapes   | 119                      | 7 (5, 2)               |
| Total          | 427                      | 37 (25, 12)            |

deliberately increase the sample size of image quality experts because we wanted to demonstrate the versatility of the proposed method. In addition, due to the insufficient sample size of image quality experts in this experiment, we were unable to find specific characteristic trends from age and gender. In our follow-up interviews with these professional imaging subjects, the male subjects stated that the difference in their observation of the image was caused by the content near the center of the image or the lines and structure in the image. The female subjects paid attention to the person in the image (if there is someone in the image), close-up, high chroma, and high brightness objects. The above characteristics will provide a reference for us to improve the algorithm.

Thinking about the limitations of objective experiments, it is not difficult to find that no matter what kind of data it is, it is difficult to avoid the gap with real human perception. Besides, review the subjective experiment limits, the experiments are all based on using the Double A 80gsm white paper for printing. The effect of this algorithm on paper of different brands, different gsm, different colors, and even different materials is still insufficient. In addition to the material being printed, this study uses the HP Office Jet 8210 with the original ink. If other printers and other brands of ink are used, the printing quality and ink-saving performance must be re-investigated.

V. CONCLUSION

In this research, we propose a toner-saving method based on human perception and CIE94 color difference model. The paper starts with background knowledge, gradually understands the algorithm, and helps explain through a large number of pictures. Our proposed method can be more clearly understood and practically applied in daily printing related fields. We expect our proposed method to help related industries improve their printing quality and reduce the energy and ink wasting. In addition to being a software algorithm, our proposed method can be applied to cooperate with existing hardware-based toner-saving method to enlarge application scope.

In the experiments, to provide more objective verification, 464 images are taken and divided into life, nature, night scene, architecture and street scene. In addition to being a material for future related papers, these images can be cited in test images for various studies. These images are available at the following link: http://web.ntust.edu.tw/~d10102106/.

Printing technology has existed for a long time, and prints are firmly related to human life. The scope of this article is currently using features that CIE94 and the human eye perceive. With the rapid development of image processing technology, this research hopes to contribute some elements to this knowledge field. Future research can be done from different perspectives, such as research from printing spots, ink printing density studies, color psychology, and so on. Besides, the color difference model is not only CIE94 but also others such as: CMC, CIEDE2000, and so on. It can also find more effective ink saving from the application scope of different color difference models and their unique characteristics.
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