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A Study of the Lightfastness of High-Chroma Water-Based Flexographic Printing Inks

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of High-Chroma Water-Based Flexographic Printing Inks

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Abstract

The study of new material for package printing is critical because packaging is not only about visual aesthetics, but also function. Technologies such as High-chroma ink that aid expanded gamut printing can be especially useful in package printing.

The thesis experiment examined the lightfastness characteristics of High-chroma water-based flexographic printing inks sets within the context of package printing applicability. Using conventional water-based flexographic printing inks as a standard, the study examined whether High-chroma inks exhibit different lightfastness characteristics. First, the researcher chose yellow and magenta process color water-based flexographic inks because of the traditional process colors, they are the least stable in terms of lightfastness characteristics. The tested yellow and magenta each have two types of lightfastness specifications which are described as fair and excellent. The inks were produced by a K-proofer to simulate the ink's solid and tint surfaces on package printing. Next, a Q-sun xenon test chamber was used to simulate environmental lighting conditions using a procedure described by ASTM International Standard Practice for Evaluating the Relative D3424-11 Method 3. After each time exposure duration, a spectrodensitometer was used to collect the density and colorimetric (L*a*b*) values of the standard ink set and High-chroma ink set. Lastly, the values were used to calculate ΔD and ΔE_{00} for analysis. The total experiment duration was 230 hours.

The results showed that there are no significant lightfastness characteristic differences between standard and High-chroma inks. The most significant difference result obtained was in the comparison of the magenta ink in fair lightfastness standard, in which the High-chroma ink exhibited better lightfastness characteristic colorimetric values than the standard ink. The results

of comparing yellow and magenta inks showed that magenta had a better lightfastness characteristic densitometric and colorimetric attributes than yellow ink. Each tested ink color exhibited unique characteristics that need to be tested and examined before implementation to fit specifics package printing requirement.

Chapter 1

Introduction and Statement of the Problem

The present chapter introduces background information, followed by the problem statement and the reasons for the researcher's interest in the topic.

Background

Packaging is a wrapping material that contains, protects, transports, dispenses, stores, identifies, and distinguishes a product (Klimchuk, 2012). Packaging panels contain typographic elements and imagery to communicate brand identity with a primary goal of generating sales. Packaging panels can be printed by various types of printing technologies dependent upon cost, volume of product, print quality, and packaging format.

Flexographic printing is a traditional printing technology that is widely used in packaging businesses because it can print on almost any type of packaging-related substrate, including sanitary folding cartons, corrugated boxes, labels, and flexible packages.

Consumer-facing printed packaging typically requires accurate brand color reproduction together with eye-catching graphics to attract customers and stand out from the great number of other products on store shelves. One solution that has gained interest in the package decoration world is expanded gamut printing, which creates a wider color gamut than typical process color printing, that is, using standard cyan, magenta, yellow, and black (CMYK) ink sets. Expanded gamut printing results in not only more vibrant process color images, but also some expanded gamut technologies purport that users can produce more accurate spot colors using process color than would be possible with traditional CMYK ink sets. For example, the ability to produce 75-

90% of the Pantone® Matching System colors without the need for special spot-color inks is reported (e.g., Baldwin, 2016; Hiremath, 2017). This ability reduces cost and set-up time to achieve accurate brand color and results in colorful impact images on the package. There are essentially two approaches to expanded gamut printing and both methods require special ink sets to achieve the wider gamut. The first begins with CMYK and adds additional process inks, so-called CMYK+ *n,* where *n* represents an additional ink or inks. A second method uses high-strength CMYK ink, known as High-chroma ink.

High-chroma ink is an ink formulation that is used for expanded gamut printing by increasing the pigment concentration relative to the other components of the ink. Users report that this type of ink provides a richer, deeper color than conventional CMYK process ink (Bogan, 2016).

Problem Statement

Implementation of expanded gamut printing inks requires an assessment of many relevant factors before adoption can be considered. For example, in addition to image reproduction concerns, the lightfastness properties of the package decoration is critical. Packages on shelves are exposed to indoor lighting environments for a period of time before they are viewed by potential consumers. Without sufficient lightfastness, the ambient light may damage printed colors causing them to wash out and potentially lose shelf-appeal. Further, if displayed next to a newer package, consumers will tend to opt for the brighter colors, considering the faded package as negative quality and freshness image (Argent, 2008).

Much of the previous research involving High-chroma ink focused on the gamut printing performance of the ink set, such as gamut reproduction comparisons between conventional

CMYK and High-chroma inks (e.g., Chung & Hsu, 2006), but found studies have not yet researched the lightfastness characteristics research of High-chroma process color ink sets. The present research seeks to examine the lightfastness characteristics of a High-chroma process color ink set using conventional CMYK lightfastness characteristics as a standard.

The research used an accelerated xenon test chamber to simulate an indoor lighting environment for packaging conditions. The purpose of this study is to determine the lightfastness characteristics of water-based flexographic High-chroma ink sets typically used in package printing.

Reason of Interest

The researcher has had work experiences as a sale representative and packaging designer in the package printing business in Thailand for six years before studying at the School of Media Sciences at Rochester Institute of Technology. The researcher became interested in expanded gamut printing technology during her study at RIT and would like to implement High-chroma printing in the future. However, one printing quality concern for the researcher is fading colors, which is one of the most common issues that she has faced in Thailand. The researcher would like to study more deeply about lightfastness characteristics of the High-chroma ink set before implementation.

Chapter 2

Theoretical Basis

The present chapter outlines the theories relevant to the topic whereas previous research is outlined in the literature review chapter. As the study is a relatively straightforward experiment involving lightfastness of printing inks, the theoretical basis is rooted in the groundwork of the scientific method. After a brief overview of these foundational works, the science which involves the quantification of color is discussed, followed by work which analyzes the impact of light on color. These three areas combined serve as the framework of the experiment.

Fundamental Scientific Method

The study is deductive in nature and a classic null hypothesis experiment. As such, it is rooted in fundamental work of scientific thinking. To many, the earliest recognition of scientific thought can be traced to the Indian sage and philosopher known as Kanada (6th to 2nd century BCE) who founded the Vaisheshika school of Indian philosophy. A detailed review of Kanada's work is beyond the scope of this analysis and interested readers are advised to consult appropriate volumes for more information here; for example, *Indian logic and atomism: An exposition of the Nyāya and Vaiçesịka systems* (Keith, 1968). In essence, Kanada speaks to that which is nameable and knowable. In the western world, it is believed that deductive reasoning was first documented by Aristotle in the fourth century BCE. Several volumes discuss these origins, among the most noteworthy is Thompson's (1975) *Aristotle's Deduction and Induction: Introductory Analysis and Synthesis.*

In 1957, W.I.B. Beveridge succinctly outlined the difference between inductive and deductive reasoning:

> Logicians distinguish between inductive reasoning (from particular instances to general principles, from fax the theories) and deductive reasoning (from the general to the particular, applying a theory to a particular case). In inductive reasoning, it starts from observed data and develops a generalization which explains the relationships between the objects observed. On the other hand, deductive reasoning starts from some general law and applies it to a particular instance (p. 84).

Others from that period who contributed to the theories which underlie widely-used deductive scientific methods include Karl Popper, Peirre Durham, Francis Bacon, and Henri Poincare (Field & Hole, 2003). Consistent among these views is the foundational structure of deductive reasoning. In the 2003 treatise "Scientific Method and Practice," Gauch writes: "A deductive argument is valid if the truth of its premises entails the truth of its conclusions, and is invalid otherwise. Many deductive systems, including arithmetic and geometry, are developed on a foundation of predicate logic in the modern and unified vision of mathematics" (p. 256). Recognizing that deductive scientific methods utilize the same logic as employed with mathematics, examples of empirical studies that are founded upon these seminal ideas abound, especially in the area of experimental research. Noteworthy recent examples that adhere to these premises include Hiremath (2018), Heng (2016), and Yu (2015).

Quantification of Color

Turning toward more recent theories which underlie the study, the theoretical basis now examines the notion of quantification of color. It is widely recognized that color perception and interpretation are subjective and that each individual defines color differently (X-Rite, Inc., 2017), but the notion of assigning numbers to colors is necessary for quantitative analyses and also builds parsimony into the manufacture of color. Therefore, the basis of widely used color quantification methods is discussed, followed by a review of those methods and colorimetric tolerancing. This theoretical basis underlies the metrics which are used in this experiment.

Munsell color system. In the western world, the current widely used notation for color quantification is rooted in the work of Albert Munsell from the early 1900s, specifically in his classic text *A Color Notation* (Munsell, 1913). Munsell broke from traditional to dimensional color models when he recognized that such systems were bound for failure. He is recognized as constructing the first widely accepted three-dimensional color system in 1905. This is known as the Munsell Color System (Berns et. al., 2000) and it quantifies the relationships of perceptual color in terms of hue, value, and chroma. Munsell plotted these in a three-dimensional "color space" in which value is mapped on the vertical axis and classifies the likeness of the color, ranging from black to white. Hue runs circularly around the value axis that distinguishes one color from another such as red, green, and blue. The notion of chroma, otherwise defined as a color's distance from gray, runs outward from the value axis toward the horizon. It describes saturation which ranges from a weak, achromatic color to a color that would be described as strong. Munsell assigned numbers to these points on a color axis and in so doing successfully defined the system that allows users to assign numbers to the attributes of color that correspond to normal human vision.

CIE standard colorimetric system. Today, the Commission Internationale de l' Eclairage (CIE) color system is the most widely used quantification of color for industrial purposes (Berns et. al., 2000). Basing their undertaking on the foundational work of Munsell and experiments involving human vision, the CIE sought to quantify a standard observer that would be useful for industrial purposes. The most popular manifestation of a CIE color space is known as L*a*b*, wherein the three attributes of color established by Munsell (value, hue, and chroma) are plotted in a three-dimensional space. Critical to the work of the CIE is the dependence of their numerical coordinates on a particular illumination. This method evolved into a measurement-based system in which a measurement device (commonly, a spectrophotometer) that captures reflectance information for a particular color sample across the visible spectrum of light. This reflectance information is mathematically converted to what are known as the tristimulus values, described as X, Y, and Z.

In the CIE standard colorimetric system, tristimulus values are converted by using spectral curve, illuminant, and standard observer. "Y" represents lightness, scaling from 0 to 100. However, X and Z do not correlate to hue and chroma. The color space has limitation in visual attributes correlation. Later, CIE established uniformity of chromaticity coordinate XYZ. It uses (x, y) to identify value (Y) known as Yxy, commonly known as the chromaticity diagram. Hue runs around the diagram and chroma is represented by a movement outward from the central white area. In 1976, tristimulus values were calculated and developed to specific L*a*b* coordinates also known as CIE L*a*b color system.

CIE L*a*b* color system. The equation that transforms the tristimulus values to become CIE L*a*b* color space is as follows:

$$L^* = 116\, f\,(Y/N_n)^{1/3} - 16$$

$$a^* = 500\,\{f\,(X/X_n)^{1/3} - f\,(Y/Y_n)^{1/3}\}$$

$$b^* = 200\,\{f\,(Y/Y_n)^{1/3} - f\,(Z/Z_n)^{1/3}\}$$ (Ohta, Robertson, and EBSCO Publishing (Firm), 2005)

The terminology of L*a*b* originated from the work of Richard Sewall Hunter, the founder of Hunter Associates Laboratory (HunterLab) in 1948. It is based on the opponent-colors theory of color vision. A single value is able to present the opponent colors which are red-green and yellow-blue. It utilizes L*, a*, and b* coordinates to locate a color. L* is described as a lightness and darkness value, ranging from 0 to 100. L* 100 is the lightest or white. a* is red and green value. +a* direction presents color toward red. In opposite, -a* runs toward green. b* is the yellow and blue value. +b* direction is toward yellow and –b* runs toward blue (X-Rite, Inc., 2017).

Color tolerancing. After establishing the coordinates which comprise the CIE L*a*b* values of a particular standard, it is convenient to reduce color difference to a single number for manufacturing purposes. This can best be thought of as putting a volume around the standard point in color space and that volume is known as Delta-E (ΔE). There are presently several equations which can be used to calculate ΔE and interested readers are advised to consult several excellent volumes germane to these discussions, including *Billmeyer and Saltzman's Principles of Color Technology* (3rd ed.) (Berns et. al., 2000), *Colorimetry: Fundamentals and applications* (Ohta, Robertson, 2005), and *A guide to Understanding Color* (X-Rite, Inc., 2017). For the purposes of the present research, ΔE equation known as ΔE 2000 will be utilized. This is consistent with much of the current work that is done by the standard committees (i.e., CIE TC1–55, CIE TC1– 57, CIE TC1– 63, CIE TC1– 81, CIE TC8– 02) (Fernandez-Maloigne, 2014) and recent researchers (e.g.,Chung et al., 2008; M. Melgosa et al., 2013; 2012). Consistent with many of these publications, ΔE 2000 will be noted as ΔE_{00} for the remainder of the thesis.

Using a color reflection spectrodensitometer, ink samples were measured both before and after exposure to accelerated fade conditions, and colorimetric values were recorded. Overall colorimetric difference was expressed using $\Delta E_{00.}$ In addition, difference in status density was recorded and noted as ΔD.

Impact of Light on Colors

In addition to the colorimetric data that is central to the experiment, the impact of light on color, particularly manufactured color, is also central to the study.

To fully understand the impact of light on manufactured color and the resultant lightfastness characteristics, a brief overview of the science of light is provided, followed by other factors that impact color fade. Afterwards, the discussion turns to the simulation of environmental characteristics in the laboratory that are widely utilized by previous researchers in this domain (e.g., Evenson, 2003; Quill, Fedor, Brennan & Everett, 2007; Wypych & Knovel (Firm), 2008).

Light is understood to be a visible part of electromagnetic spectrum. It is divided into ultraviolet light (UV), visible light, and infrared energy (IR) that have the shortest to the longest wavelength respectively. IR consists of longer wavelength than visible light at about 760 nm. UV falls at the shortest wavelengths of the spectrum at around 100 to 380 nm found on earth (Zeller+ Gmelin, NA).

The short wavelength exhibits higher energy due to higher frequency of the waves at the same speed of light in space (Pugh & Guthrie, 2001). Consequently, UV light has the highest energy among the electromagnetic spectrum. It has the ability to break chemical bonds of the molecules in objects including color. The molecules of the color absorb UV light and activate the chemical reaction of electrons leading to photochemical degradation (Evenson, 2003). The degradation visually effects discoloration or color fading.

In addition to light, there are several stimuli that influence color fade including temperature, humidity, oxygen, rainfall, contaminants, and stress (Wypych & Knovel (Firm), 2008). These stimuli influence color fading and product lifetime because of the physical and chemical reactions in molecules. It is recognized that nearly all colors will noticeably fade with sufficient exposure to normal ambient conditions, therefore the extent to which this fade can be tolerated is situation dependent. For instance, users' expectations and product lifetime should be quantified to fulfill the expectations such as durability and price, total cost of price + repair + disposal, and protection of environment worth paying for (Wypych & Knovel (Firm), 2008).

Color and product lifetime prediction using weather data interpretation is of particular importance for researchers and manufacturers. Accelerated and controlled conditions in a laboratory have the ability to quantify amounts of stimuli that affect product lifetime. Furthermore, many studies are able to develop, and achieve longer color and product lifetime to satisfy users' expectations within controlled simulation weather conditions. (Wypych & Knovel (Firm), 2008).

Light environment quantification. Q-Lab corporation develops and manufactures chambers that simulate accelerated exposure to typical environmental conditions. These chambers facilitate controlled laboratory studies that correlate to the photo degradation potential of a light source in a natural environment. Among the results of their testing is the establishment of Spectral Power Distribution (SPD), which defines “intensity of a light source as a function of the individual wavelength” (Quill, Fedor, Brennan & Everett, 2007, p.2). To achieve relevant results, several light sources are studied including outdoor sunlight and indoor window-filter sunlight with artificial light. Natural light sources were standardized by the CIE in 1989 using summer sunlight in the Northern Hemisphere intensity. The International Organization for Standardization (ISO) and American Society for Testing and Materials (ASTM) committees also use this sunlight benchmark in the test methods and specifications (Quill, Fedor, Brennan & Everett, 2007). Window-filtered sunlight, which filters out the shortest UV wavelengths, has been studied by Kodak using intensity measurement in several indoor homes and cities to get the average SPD.

Light simulation in laboratory. Light simulation devices were developed to match the actual natural conditions as closely as possible. Test chambers with xenon arc lamps are commonly used for material stability testing. xenon arc lamps are distinct from other typical manufactured lamps and can produce an excellent intensity comparable with sunlight. They produce very short wavelength which combines with multiple special glass filters to modify wavelength from the xenon lamps (Quill, Fedor, Brennan & Everett, 2007) and replicate specific actual light conditions. These can simulate wide ranges of wavelengths including UV, visible light, and IR. Thus, several industries use xenon test chambers as the product stability testing instruments.

In this thesis experiment, a xenon test chamber is used to specify appropriate SPD in specific conditions in order to quantify the lightfastness performance of the High-chroma water-based flexographic printing inks.

Chapter 3

Literature Review

This chapter presents literature relevant to the study. It begins with technical information on several aspects relevant to the research questions and concludes with previous studies that have evaluated lightfastness of printing inks in various applications. The specific areas of technical information that open the literature review include the science behind how lightfastness is tested, the nature of water-based flexographic printing inks, and information on the various methods of expanded gamut printing. From this review, the parameters of the present study are set and these parameters dictate the materials and conditions for the experiment. These include the specific material selected, the experiment design, and the subsequent evaluation procedure.

Science of Lightfastness

The science of lightfastness includes standards that have been established to consistently evaluate lightfastness, as well as the laboratory analysis of lightfastness, which includes using accelerated lightfastness testing and the subsequent evaluation.

Lightfastness standard. The most common form of calibration for lightfastness testing is the blue wool (BW) scale (Pugh & Guthrie, 2001), which is defined by the ISO. First developed for application in the textile industry, blue wool is used for scale measurement and for the performance of coloring dyes calibration. Presently, it is commonly used in the printing industry for the evaluation and specification of printing inks regarding their lightfastness. The blue wool scale is comprised of dyed wool swatches. Eight different wool swatches are dyed in such a manner that they exhibit different levels of fading; manufactured printing inks are compared to these wool swatches and marketed accordingly for various applications. The specific technical details of the blue wool testing procedure are beyond the scope of the present review, interested readers are advised to consult Pugh and Gutherie (2001) for specifics on the dying procedures and methodologies employed. The test involves exposing the dyed blue wool (BW) patches to a number of stimuli and recording the results. With commercial printing inks, the blue wool standard rating is used to communicate the lightfastness characteristics of the commercial inks with users. The standard rating begins at BW1, which represents the least lightfastness, and extends to BW8, which represents the most lightfastness. In practical use, BW1 through BW3 represents poor lightfastness, BW4 and BW5 represent fair lightfastness, BW6 represents good lightfastness, and BW7 and BW8 represent excellent lightfastness (Pugh & Guthrie, 2001).

Flexographic printing for packaging commonly uses fair to higher lightfastness standard (BW5 and BW6) because packaging typically is stored and used in an indoor environment. There are limitations of handling very high lightfastness inks because of some physical characteristics that affect the visual quality of printing, especially for yellow and red pigments (Roth, J., personal communication, October 19^{th}, 2017). Printing inks with high lightfastness characteristics can be problematic as they typically have lower transparency, lower color strength, are not as pure, and are higher in cost than those with low lightfastness characteristics (Graphix Essential, 2010).

Accelerated lightfastness conditions. Accelerated lightfastness testing allows for the rapid evaluation of lightfastness characteristics by controlling the environment and lighting in such a manner that samples will fade in a relatively short period of time as if they were exposed to prolonged conditions. An example is shown in Table 1. It demonstrates a correlation between outdoor sunlight exposure times provided by Flint Group company (2001), and the exposure times in the outdoor condition in the test chamber (IPA, 2008) using the BW scale reference.

Table 1.
Indication of lightfastness in relation to the amount of time that ink is exposed under the outdoor sunlight in different time of the year

BW scale	3	4	5	6	7	8	
June-July-August	4	8	18	35	71	142	days
April-May-September	12	25	50	100	201	403	days
March-October-November	25	50	100	200	400	800	days
December-January-February	75	150	300	600	1200	2400	days
Test chamber	5	10	20	40	80	160	hours

The accelerated lightfastness procedure is controlled to achieve end-use product environment and provide a consistent result. The following list shows the conditions that need be monitored to achieve uniform lightfastness experiment results, as provided by Pugh & Guthrie (2001):

1. The spectral distribution of the light source
2. The intensity of the light source
3. The distance of the light source from samples
4. Relative humidity
5. Samples preparation
6. Duration of the test
7. Ambient temperature
8. Sample temperature, achieved from the back-panel indicator in the chamber

The specific conditions for a given test are dictated by a typical application environment of the printing product evaluated, such as magazines, billboards, and packaging. ASTM

International establishes a Standard Practice for Evaluating the Relative Lightfastness and Weatherability of Printed Matter (2011) known as Designation: D3424-11. It states the standard methodologies for the determination of relative lightfastness and weatherability of printed matter under eight conditions. For example, Method 3 is the procedure that is used for xenon-arc apparatus with window glass filters to simulate daylight behind window glass. It is used in Lind, Stack & Everett's (2004) study[1], and advances a methodology for the lightfastness of printing inks for indoor use. Specific conditions are described in the discussion of applied lightfastness later in the paper.

Lightfastness evaluation. Color changes after exposure are periodically visually and instrumentally evaluated using unexposed and exposed samples (ASTM International, 2011). The exposure intervals are specified durations of time, duration of UV exposure, and the number of intervals that depend on the required lightfastness determination. For instrumental evaluation, a spectrophotometer is used to measure L*a*b* data of the samples. The color changes are determined using unexposed and exposed sample's data to calculate ΔE_{00} for every required time interval. The results are collected and plotted to evaluate the correlation between color change as expressed in ΔE_{00} and time intervals. This evaluation method is more accurate than a single measurement because the lightfastness characteristic is not linear. Additional appearance changes of the inks after exposure are also investigated, such as crazing, blistering, and delamination (ASTM International, 2011).

Having discussed literature relevant to lightfastness, the review will now discuss literature relevant to water-based flexographic printing inks.

[1] Lind, et.al. (2004) is discussed in detail beginning on page 21 of the present thesis.

Nature and Application of Water-Based Flexographic Inks

In understanding water-based flexographic printing inks, the present review begins with a discussion of those components which comprise all typical printing inks. Then, a discussion of water-based flexographic printing ink in particular will be conducted, followed by a review of pigments which are the typical colorant in these inks. A discussion of the application of these inks, specifically in regard to expanded gamut printing processes and the details of the High-chroma expanded gamut printing inks, completes the present section.

Printing ink. Printing ink consists of colorants, vehicles, additives, and carrier substances to form ink properties (Kipphan, 2001). The structure and components of printing inks are dependent upon an ink transfer mechanism and types of drying and fixing of the ink on the substrate. There is significant variability in the properties of the inks with regard to flow characteristics. For example, gravure printing utilizes low viscosity liquid ink to fill the gravure cylinder cells at high printing speeds. The drying process can be evaporation of solvents or radiation cross-link depending on the carrier substances. On the other hand, lithographic printing uses the high viscosity of the paste-like oil-based ink required for the process. The ink is not intended to dry during a transfer process from a printing plate to a blanket roller. Chemical reaction such as cross-link and oxidation is used in the drying process after images are transferred to substrates.

Flexographic printing inks. Flexographic printing technology dominates the package printing industry largely due to its ability of printing on a wide variety of substrates, such as a corrugated box, flexible packaging, and label stock. Flexographic printing uses raised flexible printing plates, with inking unit that typically consists of a doctor blade containing an anilox roller and an impression roller. Flexographic inks have a low viscosity and exhibit fast drying characteristics. Pigments are generally used as a colorant that is beheld in suspension in the based liquid, which can be ethyl acetate, alcohol, and water. Rentzhog (2004) notes that dyes are used as colorants in some special applications.

Water-based flexographic printing inks. Water-based flexographic printing inks are widely used for package printing (Kipphan, 2001). As their categorical name suggests, water is used as a carrier substance in the ink formulation. Alcohol is added to support better adhesion to the substrates. Water-based flexographic printing inks were first introduced in the 1930s and were established in commercial use for paper and paperboard in the 1950s. In the 1980s, there was an increased awareness of safety and environmental concerns, which were being more strictly regulated: this facilitated the further adoption and development of water-based flexographic printing (Rentzhog, 2004). Today, water-based flexographic printing inks are extensively used in many applications. According to a flexographic printing ink market trend report by Global flexographic printing inks (water-based, solvent-based and UV-cured) market - industry analysis, size, share, growth, trends and forecast, 2014 - 2020. (2014), water-based flexographic printing inks' market share led the overall industry in 2015. The global flexographic printing inks market was valued at USD 6.41 billion in 2013 and is anticipated to reach USD 9.32 billion by 2020. The water-based flexographic printing inks segment accounted for over 40% of the global flexographic printing inks market share in 2013.

Nature of pigments. Colorants are divided into two types, which are pigments and dyes. They provide the color that is, the visual identity of the inks. Pigments can be organic or inorganic compounds of solid particles that are insoluble in liquid base. Printing inks typically contain pigments because they normally exhibit a better lightfastness and more stable ink impression than dyes (Kipphan, 2001). The pigments scatter and absorb specific wavelengths of the visible light (400-700 nm) to present colors (FIRST 5.1, 2015). For example, pigments such as organic Ultramarine in water-based ink absorbs red and green light, but scatters blue light, creating an appearance of blue. Ten percent of the pigment molecules on the surface along with some influence from molecules beneath the surface is impacted by the light (Kipphan, 2001). Light absorption by the pigments of the printing ink is the determinant of lightfastness. Light breaks chemical bonds of the pigment particle then photochemical degradation occurs. In the case of the natural ultramarine pigment, red and green absorbance will degrade the pigment and visually fade over time.

In addition to a pigmentation, the density of the ink will influence lightfastness. Pigments with higher density will increase the lightfastness characteristics because they will have more pigment particles to withstand the destructive influence of light. On the other hand, inks with transparent white tend to fade rapidly into white because they have less concentration of pigments (Pritchard, 2010). In this case, solid printing and halftone printing can have an affect on the lightfastness characteristics because the nature of the halftone screen is that it reduces ink density, to visualize a lower color tone. It is suggested that comprehensive lightfastness testing in addition to solids should include a tint value as well.

Furthermore, each color pigment has different lightfastness characteristics because it consists of different chemical components which effect its ability to absorb and scatter light at specific wavelengths (Völz, 2001). Specifically, black ink, which is made from organic pigments of carbon black, is strongly stable under sunlight and also protects substrates under it. Moreover, process color cyan is made from organometallic compounds that are nearly as stable as carbon black. It is widely recognized that of the typically used process colors, black and cyan exhibit higher lightfastness than magenta and yellow. Black and cyan will fade only slightly during the same time that it takes yellow and magenta to fade noticeably (Roth, J., personal communication, October 19, 2017). Magenta absorbs visible green light (495 nm- 570nm) which occupies a more extensive range in a visual light spectrum than other colors. It is more noticeable than others after degradation. Yellow absorbs visible blue light (450 nm- 495 nm) which typically has the highest energy among visible light. Lucas (2001) notes that yellow will show more significant discoloration than other process colors.

Expanded Gamut Printing

Expanded gamut printing processes purport to provide a wider color gamut than the traditional CMYK printing process. Expanded gamut printing can take multiple forms, one form of which uses additional process color inks along with the traditional cyan magenta yellow and black process inks, (so-called CMYK + *n*) and another form uses CMYK ink sets that are more highly pigmented than traditional CMYK inks. Expanded gamut printing technology assists printers in their desire to better manage brand colors as the technology allows the printers to present more accurate brand color reproduction without the need for costly spot colors. A study by Bogan (2016) states that graphics and colors on packaging play a meaningful role with customers. They essentially dictate consumers' brand recognition and perception. Furthermore, a study by Singh (2006) noted that "People make up their minds within 90 seconds of their initial interactions with [products]. About 62–90% of the assessment is based on colors alone." Highly saturated colors on packages are desirable as they allow the brand to attract customers and facilitate buying decisions at the point of purchase. As a result, the ability to reproduce highly saturated colors, along with the accurate color reproduction enabled by expanded gamut printing technology, benefits brand management for businesses.

Hiremath (2017) outlines techniques to achieve expanded color gamut in printing as:

1. Change of substrate;
2. Number of primaries;
3. Amount of ink film thickness;
4. Increase pigment concentration;
5. Type of screening.

With one or a combination of the techniques outlined above, printers strive to provide a greater color range than with traditional process printing technology. As previously indicated, increasing pigment concentration is one example of an expanded gamut printing methodology that achieves a broader color gamut without adding special ink to the process color set. This method uses unique ink sets called High-chroma ink sets of CMYK process colors.

High-chroma ink is a high tint strength ink that provides a stronger and more vibrant color than conventional ink at lower ink film thickness. High-chroma ink consists of a high concentration with smaller pigment particles than a traditional ink (Pugh & Guthrie, 2002). Chung & Hsu (2006) studied the possibility to expand gravure printing color gamut by increasing pigment concentration. The result shows that a high concentration pigment ink provides a larger gamut than the conventional pigment ink. The researchers note a significant improvement in color gamut after using High-chroma ink at yellow, green-yellow, and red-yellow regions.

It is important to recognize that physical properties such as the particle size and the particle concentration of the High-chroma pigment that can affect the lightfastness of the ink. A study by Giles, Walsh & Sinclair (1977) compares the lightfastness characteristics of the large and small particles of Pigment Orange 36. The outcome demonstrates a higher lightfastness characteristic in the larger pigment particle size with a similar pigment concentration. Moreover, Pritchard (2010) studied the relationship between pigment concentration and the lightfastness characteristics. The results showed that higher concentration of the pigment particle can provide a higher lightfastness characteristic because it consists of a more significant number of pigment particles to withstand the destructive influence of light.

Much of the specification information surrounding High-chroma inks are not assessable as they are patent-protected and considered proprietary by the ink companies which develop these technologies. In this study, the researcher has chosen to work with water-based flexographic inks at different levels of lightfastness and pigmentation as marketed by the Flint Group company, as representative of commonly used ink sets.

Applied Lightfastness in Printing

Previous lightfastness research studied lightfastness of inks from different perspectives and in varying conditions. After an extensive review of literature, several studies were found that examined lightfastness of both conventional printing inks and digital printing inks. Relevant studies to this application are subsequently reviewed.

Lightfastness testing in conventional printing technology. Conventional flexographic and offset lithographic printing inks' lightfastness characteristics studies are reviewed, and their accelerated light exposure conditions and evaluation procedures will be replicated in the present study. The reviewed studies follow.

Lind, Stack & Everett (2004) studied lightfastness of lithographic inks. The purposes of the study were to quantify the lightfastness of conventional lithographic inks in worst case environmental conditions, create an acceptable lightfastness experiment standard of inks, and provide a suitable methodology to evaluate ink performance. The researchers compared different models of a Q-Sun Accelerated Fade with the goal of assessing the exposure equipment. Eight different lithographic ink colors were used including magenta, violet, orange, red, purple, and three different yellows.

ASTM D3424 (Standard Test Methods for Evaluating the Relative Lightfastness and Weather ability of Printed Matter) method three was selected to be used in the Lind, et al study. The conditions simulated daylight behind window glass using a window glass filter. The filter cuts off the shortest UV wavelength by dirt, thickness, tint, lamination, or double panel of the filter (Quill, Fedor, Brennan & Everett, 2007). Irradiance level was set at 0.55 W/m^2 Nm (± 0.02 W/m^2. nm), and the nominal cut-on of 340 nm. Relative humidity is at RH = 50%. The exposure cycle was set for continuous light at 63 ± 3°C (145 ± 5°F). Test intervals were set at one month (720 hours) and total radiant exposure was set at 1473 kJ/m^2 at 340 nm. The lightfastness results were measured using colormetric measurement instrument then the ΔE was plotted on the graph that showed the correlation between ΔE and exposure time.

There were only small changes for all of the inks during the first 24 hours and the inks behaved differently in terms of color change as the time progressed. However, almost all of the color established similar S-curve shape graphs and they fluctuated in the middle of intervals. Only excellent lightfastness inks exhibited low ΔE with low linear slope graphs throughout the experiment.

For the precise instrument determination result, both of the Q-Sun Xe-1 and Xe-3 models were able to discriminate the good lightfastness inks from bad lightfastness inks. Initially, three yellow inks in the experiment had similar appearance. After the exposure, they effectively differentiated the yellow ink designed for outdoor application from the others. The authors noted that RH control function did not make a significant difference between Xe-1 and Xe-3.

Bates, Zjakić & Milković (2011) sought to determine lightfastness and weatherfastness of flexible package printing materials. One key purpose of the study was to investigate the best lightfastness of the precise substrates and inks that are used in the flexible packaging industry. Solvent-based Ultraviolet (UV) and Electron Beam (EB) curable flexographic printing inks were printed on flexible plastic materials i.e., polyvinyl chlorides (PVC), and oriented polypropylene (OPP). The study focused on color changes of process colors overprinted pattern of blue (cyan + magenta), green (yellow + cyan), and red (yellow + magenta).

Bates et.al. (2011) utilized xenon lamps with and without artificial rain, and Xenotest Alpha test chamber was used to simulate daylight exposure consistent with the ISO12040 standards (Prints and printing inks—Assessment of lightfastness using filtered xenon arc light). The radiation was 200 to 800 nm at 5500 K - 6500 K. The researchers examined the effects of different relative humidity with and without artificial rain. Each condition duration was one interval of 72 hours. The samples and BW scale were partially covered with a non- transparent aluminum plate and stored in the Xenotest chamber.

In evaluating the results, Bates et. al. (2011) utilized thirty participants and evaluated visual impressions together with instrument-based analyses. The lightfastness and weatherfastness were determined by comparing the change degrees with the eight BW references. The degrees are classified as follows: 1 = very poor; 2 = poor; 3 = moderate; 4 = fairly good; 5 = good; 6 = very good; 7 = excellent; 8 = maximum lightfastness (Pugh & Guthrie, 2001). Instrument measurement using relative reflection was used with an interval of the wavelengths from 400 nm to 750 nm.

The color determination results showed a better lightfastness in solvent-based inks than with UV curable inks in both substrates. This was consistent with both visual evaluation and instrument measurement. However, ΔE calculation results could identify lightfastness characteristic of ink more delicately than eight degrees of BW subjective assessment rating. Possibly, inks that have similar BW ratings may exhibit different ΔE values. Therefore, instrument analysis was deemed necessary for critical lightfastness evaluation.

Lightfastness testing in digital printing technology. Two relevant studies were found that analyzed the lightfastness of digital printing inks. These are applicable to the present study as they help to validate the methodology.

International Prepress Association (IPA) Digital Print Forum (2008) determined lightfastness of CMYK process color dyes using the output from eight different digital presses, i.e., HP Indigo 3050, HP Indigo 5000, HP indigo 5500, Kodak NEXPRESS S3000, Konica Minolta bizhub PRO C6500, Xeikon 6000, Xeikon 8000, and Xerox iGen3 110. The conventionally-pigmented inks for offset lithography were used as a lightfastness baseline. The Q-Sun Xe-1 device and ASTM standards for outdoor Method 2 for outdoor weathering were used to simulate outdoor exposure at a high radiation activity. The international standards ISO 2835 and ISO 12040 were referenced. A time duration referred to the BW scale 8 is considered equivalent to 160 hours' exposure with the outdoor condition in the Q-Sun chamber, and 18 months of summer sunlight. Time intervals were divided into eight periods of BW scale rating, i.e., 5, 10, 20, 40, 80, 160 hours in the test chamber with outdoor simulation conditions.

The study utilized both spectrophotometric and densitometric readings for instrumental measurement evaluation. Density and ΔE changes were used to evaluate the results. For the offset lithography samples, yellow and magenta exhibited the most significant ΔE values. The digital printing ink samples showed a much lower ΔE than the offset lithographic printing inks. It was noted that some of the digital printing ink samples started significantly fading after 40 - 80 hours.

Yellow and magenta offset lithographic samples exhibited a strong decline in density. On the other hand, cyan and black were mostly stable. All of the digital printing samples were practically stable in ink density, especially the samples from Kodak NEXPRESS and Xeikon 6000. HP presses samples showed a gradual decline in density for every ink. Changes in ΔE were in direct proportion to the density changes. In summary, the higher the ΔE, the more drastic was the decline in density and the colorants. The digital presses showed a better lightfastness than conventional offset lithographic colorants.

In a similar study entitled *Colorfastness of reactive inks versus pigment inks on digital textile printing,* Thompson (2016) determined colorfastness of digitally printed reactive and pigment inks printed on fabrics. The purpose of the study was to investigate fade resistant characteristics of the reactive inks for digital printing that are widely used in the textile industry. Fabric swatches were digitally printed with a red, blue, and green geometric pattern using both reactive and pigment inks. Five different cotton fabrics were used as substrates.

The samples were tested using the American Association of Textile Chemists and Colorists (AATCC) grayscale and nine-step chromatic transference scale serving as the textile testing standard. In addition to light exposure conditions, other tests were used to simulate laundering, crocking, perspiration, and light exposure conditions. For the lightfastness testing, the study used a xenon-arc chamber. The conditions applied continuous light with the black panel temperature at 63 ± 1°C, the chamber air temperature at 43 ± 2°C, and humidity at 30%. Time duration was eight hours using BW scale standard to determine the amount of time. The evaluation used CIE L*a*b* to calculate ΔE, and it obtained the AATCC grayscale and nine-step chromatic transference scale rating of visual assessment. The result showed that pigment inks exhibited a less color change than reactive inks after laundering, crocking, and perspiration. Both of the inks were almost stable from the light impact.

As illustrated from the above studies, there is ample research on lightfastness as applied in the printing industry, no study was found that examined water-based flexographic inks regarding lightfastness after an extensive search of the academic literature. Furthermore, no found research evaluated the lightfastness of High-chroma inks, which are especially conducive to expanded gamut printing techniques. The review of fade-resistance studies of inks in the present literature review chapter serve to assist the researcher in terms of clarifying the scope of this thesis experiment. Materials, equipment, procedure, and evaluation methodologies from the previous studies are considered to specify the parameters used to conduct the present thesis experiment.

In this thesis experiment, the researcher sought to determine lightfastness characteristics of yellow and magenta High-chroma water-based flexographic printing inks using respective conventional water-based flexographic printing inks as a baseline. This research sought to replicate the accelerated conditions of the Lind, Stack & Everett (2004) study using ASTM standard method 3 which utilized a xenon-arc apparatus with window glass filters to simulate daylight behind window glass. The details of the conditions used will be explained in the methodology chapter. The evaluation of the experiment will be instrument-based analyses. Both ΔE_{00} and density difference (ΔD) will be used to calculate color changes, consistent with the IPA Digital Print Forum (2008) study. Correlations between ΔE_{00} and ΔD are noted.

Chapter 4

Research Objectives

The thesis experiment determined the lightfastness characteristics of High-chroma water-based flexographic printing inks sets. Using conventional water-based flexographic printing inks as a standard, the study examined whether High-chroma inks exhibit different lightfastness characteristics. It is believed that the analysis is timely as both academic and trade literature suggest that there is an increased interest in expanded gamut printing, and one method of achieving expanded gamut is to use High-chroma inks. Furthermore, water-based flexographic printing is widely used in the packaging sector. Although an extensive review of the literature found numerous studies that evaluated lightfastness of printing inks, no found study examined High-chroma, water-based flexographic printing inks in this context. As previous research indicates, process magenta and yellow inks are more likely to fade than process cyan and black, thus the study limits evaluation to magenta and yellow. Both standard and High-chroma printing inks are evaluated using established accelerated lightfastness testing methods for changes in both status density (ΔD) and colorimetric change (ΔL^*, Δa^*, Δb^* and ΔE_{00}).

Research Questions

The research questions are as follows:

1. Is there a difference in the lightfastness characteristics of the solids of process yellow and magenta ink sets between standard and High-chroma inks?
    1.1. After exposure to accelerated fade conditions, is the change in status density (ΔD) the same between yellow standard and High-chroma inks solids?
    1.2. After exposure to accelerated fade conditions, is the change in colorimetric values (ΔL^*, Δa^*, Δb^* and ΔE_{00}) the same between yellow standard and High-chroma ink solids?
    1.3. After exposure to accelerated fade conditions, is the change in status density (ΔD) the same between magenta standard and High-chroma inks solids?
    1.4. After exposure to accelerated fade conditions, is the change in colorimetric values (ΔL^*, Δa^*, Δb^* and ΔE_{00}) the same between magenta standard and High-chroma ink solids?
2. Is there a difference in the lightfastness characteristics of the tints of process magenta and yellow ink sets between standard and High-chroma inks?
    2.1. After exposure to accelerated fade conditions, is the change in status density (ΔD) the same between yellow standard and High-chroma ink tints?
    2.2. After exposure to accelerated fade conditions, is the change in colorimetric values (ΔL^*, Δa^*, Δb^* and ΔE_{00}) the same between yellow standard and High-chroma ink tints?
    2.3. After exposure to accelerated fade conditions, is the change in status density (ΔD) the same between magenta standard and High-chroma ink tints?

2.4. After exposure to accelerated fade conditions, is the change in colorimetric values (ΔL^*, Δa^*, Δb^* and ΔE_{00}) the same between magenta standard and High-chroma ink tints?

3. Is there a difference in the lightfastness characteristics between magenta and yellow standard inks?

   3.1. After exposure to accelerated fade conditions, is the change in status density (ΔD) the same between standard yellow and magenta ink solids?

   3.2. After exposure to accelerated fade conditions, is the change in colorimetric values (ΔL^*, Δa^*, Δb^* and ΔE_{00}) the same between standard yellow and magenta ink solids?

4. Is there a difference in the lightfastness characteristics between magenta and yellow High-chroma inks?

   4.1. After exposure to accelerated fade conditions, is the change in status density (ΔD) the same between High-chroma yellow and magenta ink solids?

   4.2. After exposure to accelerated fade conditions, is the change in colorimetric values ((ΔL^*, Δa^*, Δb^* and ΔE_{00}) the same between High-chroma yellow and magenta ink solids?

Table 2. *Sets of comparison in the research questions (RQs) of the thesis experiment*

Research Question		Comparison sets		Comparison values
RQ1.	RQ 1.1	Yellow standard ink	Yellow High-chroma ink	ΔD solid
	RQ 1.2	Yellow standard ink	Yellow High-chroma ink	ΔL*, Δa*, Δb*, and ΔE_{00} solid
	RQ 1.3	Magenta standard ink	Magenta High-chroma ink	ΔD solid
	RQ 1.4	Magenta standard ink	Magenta High-chroma ink	ΔL*, Δa*, Δb*, and ΔE_{00} solid
RQ2.	RQ 2.1	Yellow standard ink	Yellow High-chroma ink	ΔD tint
	RQ 2.2	Yellow standard ink	Yellow High-chroma ink	ΔE_{00} tint
	RQ 2.3	Yellow standard ink	Yellow High-chroma ink	ΔD tint
	RQ 2.4	Yellow standard ink	Yellow High-chroma ink	ΔE_{00} tint
RQ3.	RQ 3.1	Yellow standard ink	Magenta standard ink	ΔD solid
	RQ 3.2	Yellow standard ink	Magenta standard ink	ΔL*, Δa*, Δb*, and ΔE_{00} solid
RQ4.	RQ 4.1	Yellow High-chroma ink	Magenta High-chroma ink	ΔD solid
	RQ 4.2	Yellow High-chroma ink	Magenta High-chroma ink	ΔL*, Δa*, Δb*, and ΔE_{00} solid

Hypotheses

Based on the objectives and research questions of the study, hypotheses are stated as follows:

1. Research question one:

1.1. H_0: $\Delta D_{\text{Standard yellow solid}} = \Delta D_{\text{High-chroma yellow solid}}$,

H_1: $\Delta D_{\text{Standard yellow solid}} \neq \Delta D_{\text{High-chroma yellow solid}}$

1.2. H_0: $\Delta D_{\text{Standard magenta solid}} = \Delta D_{\text{High-chroma magenta solid}}$,

H_1: $\Delta D_{\text{Standard magenta solid}} \neq \Delta D_{\text{High-chroma magenta solid}}$

1.3. H_0: $\Delta E_{00\ \text{Standard yellow solid}} = \Delta E_{00\ \text{High-chroma yellow solid}}$,

H_1: $\Delta E_{00\ \text{Standard yellow solid}} \neq \Delta E_{00\ \text{High-chroma yellow solid}}$

1.4. H_0: $\Delta E_{00\ \text{Standard magenta solid}} = \Delta E_{00\ \text{High-chroma magenta solid}}$,

H_1: $\Delta E_{00\ \text{Standard magenta solid}} \neq \Delta E_{00\ \text{High-chroma magenta solid}}$

2. Research question two:

2.1. H_0: $\Delta D_{\text{Standard yellow tint}} = \Delta D_{\text{High-chroma yellow tint}}$,

H_1: $\Delta D_{\text{Standard yellow tint}} \neq \Delta D_{\text{High-chroma yellow tint}}$

2.2. H_0: $\Delta D_{\text{Standard magenta tint}} = \Delta D_{\text{High-chroma magenta tint}}$,

H_1: $\Delta D_{\text{Standard magenta tint}} \neq \Delta D_{\text{High-chroma magenta tint}}$

2.3. H_0: $\Delta E_{00\ \text{Standard yellow tint}} = \Delta E_{00\ \text{High-chroma yellow tint}}$,

H_1: $\Delta E_{00\ \text{Standard yellow tint}} \neq \Delta E_{00\ \text{High-chroma yellow tint}}$

2.4. H_0: $\Delta E_{00\ \text{Standard magenta tint}} = \Delta E_{00\ \text{High-chroma magenta tint}}$,

H_1: $\Delta E_{00\ \text{Standard magenta tint}} \neq \Delta E_{00\ \text{High-chroma magenta tint}}$

3. Research question three:

3.1. H_0: $\Delta D_{\text{Standard yellow}} = \Delta D_{\text{Standard magenta}}$,

H_1: $\Delta D_{\text{Standard yellow}} \neq \Delta D_{\text{Standard magenta}}$

3.2. H_0: ΔL^*, Δa^*, Δb^*, and $\Delta E_{00\ \text{Standard yellow}}$

$= \Delta L^*$, Δa^*, Δb^*, and $\Delta E_{00\ \text{Standard magenta}}$,

H_1: ΔL^*, Δa^*, Δb^*, and $\Delta E_{00\ \text{Standard yellow}}$

$\neq \Delta L^*$, Δa^*, Δb^*, and $\Delta E_{00\ \text{Standard magenta}}$

4. Research question four:

4.1. H_0: $\Delta D_{\text{High-chroma yellow}} = \Delta D_{\text{High-chroma magenta}}$,

H_1: $\Delta D_{\text{High-chroma yellow}} \neq \Delta D_{\text{High-chroma magenta}}$

4.2. H_0: ΔL^*, Δa^*, Δb^*, and $\Delta E_{00\ \text{High-chroma yellow}}$

$= \Delta L^*$, Δa^*, Δb^*, and $\Delta E_{00\ \text{High-chroma magenta}}$,

H_1: ΔL^*, Δa^*, Δb^*, and $\Delta E_{00\ \text{High-chroma yellow}}$

$\neq \Delta L^*$, Δa^*, Δb^*, and $\Delta E_{00\ \text{High-chroma magenta}}$

Following the steps outlined in the methodology chapter, the research sought to address the above mentioned research questions with the goal of contributing to the literature in this domain.

Chapter 5

Methodology

This chapter reviews the methodology used to address the research questions. It begins with an overview and a figure that outlines the research steps. Then, it reviews the equipment used as well as the materials. Finally, data collection and analysis are examined.

Overview

The research utilized both standard and High-chroma magenta and yellow water-based flexographic printing inks. These inks were obtained from Flint Group company for the experiment. As it is important to test the inks in conditions representative of standard printing, ink proofs were made using a K-proofer, which is a specially designed ink proofing device for liquid printing inks. The ink proofs were made on a standard Leneta paper which is commonly used for this purpose. Moreover, the ink proofs represented both solid and tint values. Multiple proofs of each ink and condition were made, and some were subject to accelerated fade conditions while others were stored to act as a control. The control acting samples were stored in light proof containers after the ink proofs were produced and dried.

All samples were measured for both densitometric and colorimetric values using a spectrophotometer. The proofs subject to accelerated fade conditions were placed in a xenon test chamber for ultraviolet exposure in which the exposure conditions were designed to simulate an indoor lighting environment. Using a standardized test procedure (Lind, Stack & Everett, 2004), the proofs in the accelerated fade cabinet were measured periodically. ΔD and ΔE_{00} were analyzed to address the research questions.

Thesis Research Steps

Workflow diagram is shown in Figure 1 which describes the steps in this research.

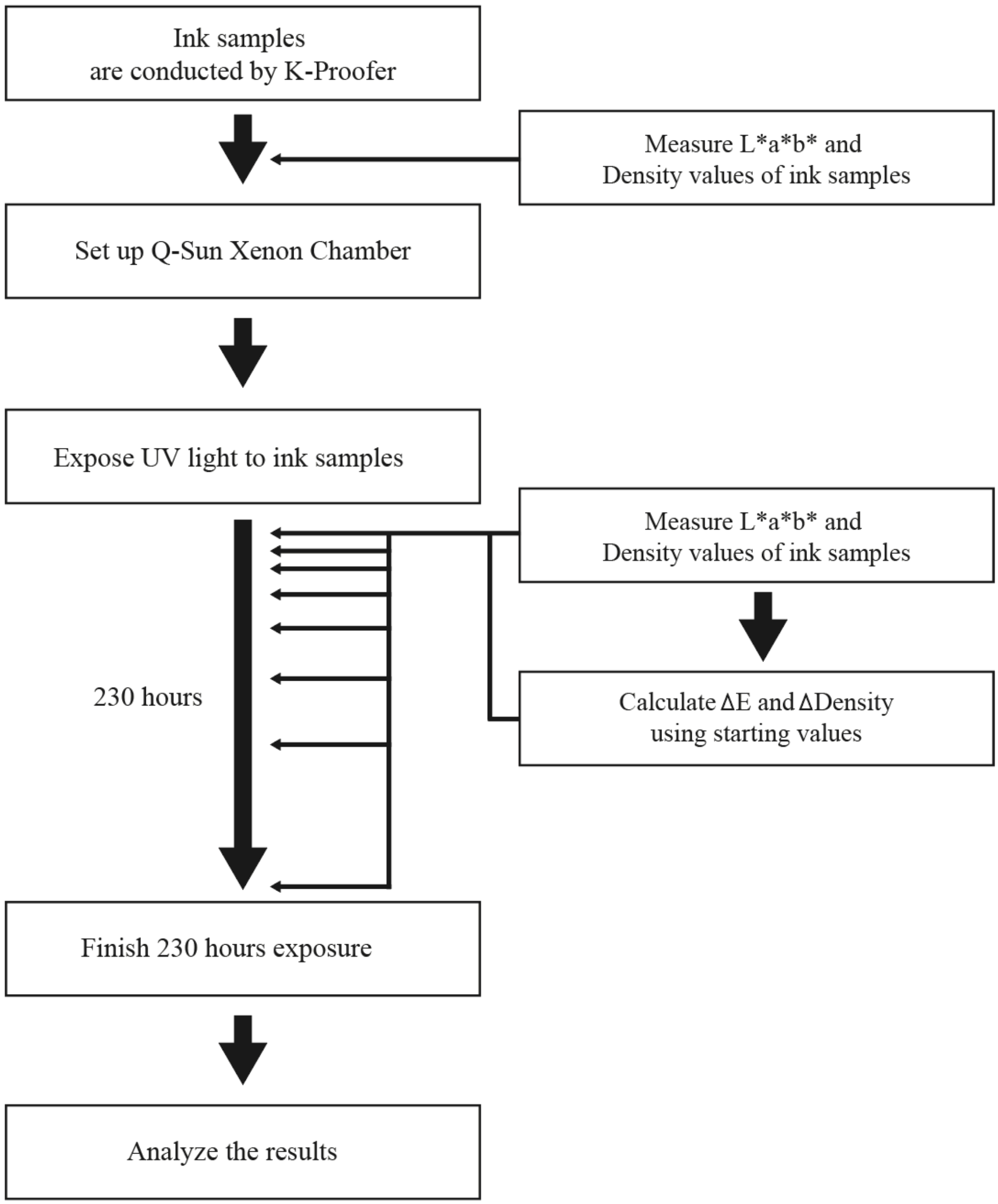

Figure 1. *Workflow diagram of research steps*

Equipment

The following equipment was used: K-proofer, spectrodensitometer, and Q-sun xenon chamber to conduct the experiment.

K-proofer. The K-proofer is a printing proofer used to create proofs of ink samples in such a manner that they replicate typical printing conditions without the cost and complications involved in an actual press run. The device uses an electronically engraved printing plate which replicates solids as well as tint values. For the thesis experiment, the solid ink (100%) along with a 45% tint was used.

Spectrodensitometer. A single spectrodensitometer was utilized for all measurements in the thesis experiment. The device was a Techkon SpectroDens Premium, which was calibrated before each reading. By using a single device, inter-instrument agreement issues were minimized. This device took spectral readings and calculated both densitometric and colorimetric information. The study reported Status-T density and density difference (ΔD) as well as colorimetric data (L*, a*, b*) and colorimetric difference (ΔE_{00}). The specific colorimetric parameters are presented later in the present chapter.

Q-Sun xenon chamber. A xenon test chamber, manufactured by Q-Sun, was used for the accelerated fade testing. The chamber simulates the damage caused by UV light exposure, temperature, and humidity. It accelerates the damage from the natural atmosphere to not only obtain faster results, but also gives researchers a more controlled environment to support repeatability. The specific settings used for the Q-Sun cabinet are outlined later in the present chapter.

Experiment

This section describes the experimental variables, methodology to conduct the experiment, data collection, and the method to analyze the results.

Experimental variables. The experiment was comprised of control, independent, and dependent variables.

Control variables. The control variables in this thesis experiment consisted of the initial ink samples and the conditions in the Q-Sun xenon chamber controlled with specific values.

Initial ink samples. The ink sets in the thesis experiment consisted of the standard water-based flexographic ink set and the High-chroma water-based flexographic ink sets. In each set, there were magenta and yellow process inks and each of them had two distinctive lightfastness characteristic inks that were described as "fair" and "excellent". Viscosity of the inks was 1.0 Poise indicated by using Zahn viscosity cup No. 3 for 12 seconds.

Table 3
Inks used in the experiment provided by Flint Group company

Standard water-based flexographic ink			
Color code	Pigment	Color	BW scale
HMC10081	Yellow 74	Yellow	6
HMC10035	Yellow 194	Yellow	7
HMC30080	Red 57:1	Magenta	4
HMC30008	Red 117	Magenta	7

High-chroma water-based flexographic ink			
Color code	Pigment	Color	BW scale
HMR10081	Yellow 74	Yellow	6
HMR10035	Yellow 194	Yellow	7
HMR30080	Red 57:1	Magenta	4
HMR30008	Red 117	Magenta	7

Leneta printing ink drawdown 3NT-34 was used as the substrate. This substrate is widely used for ink proofing purposes and is made with minimal optical brightening agents (OBAs). OBAs are additives used to increase the paper brightness, but these will break down over time and causes color shifts (Roth, J., personal communication, October 19th, 2017). Substrates without OBA provide lower color shifts in lightfastness testing and also show the best fade-resistant performance (Lovell, Fleming III & Carlick, 2016). The K-Proofer was used to produce the ink samples. Each ink sample consisted of two density values which were 100% and 45% using a resolution of 150 lines per inch. After producing the ink samples, they were stored in the stored in a lightproof bag to protect them from exposure to natural and UV light before the experiment started.

Q-Sun Conditions. The researcher utilized the following specific conditions on the Q-Sun:

- Filter = window glass filter
- Irradiance level = at 1.10 W/m^2. nm (± 0.02 W/m^2. nm)
- Nominal cut-on of 420 nm.
- Relative humidity is at RH = 50%
- Temperature = Continuous Light at 63 ± 3°C (145 ± 5°F)
- Test intervals = maximum 230 hours

Samples were mounted in the standard distance defined by the test chamber. The uninsulated black panel monitored the temperature and relative humidity in the chamber. Samples in the chamber were rotated 180° after each iteration of the exposure to average the humidity and temperature. This procedure was suggested by Pugh & Guthrie (2001) with the goal of preventing the samples from becoming overheated. Moreover, every sample was equally exposed to the light and other conditions in the Q-Sun.

Independent and dependent variables. The independent variables for the experiment was exposure time intervals from five hours to a maximum 230 hours.

The dependent variables were color and density changes of the samples in different inks and dot screen simulation. The value was shown in ΔD and ΔE_{00} values. They were calculated by using the initial ink samples and exposure samples values.

Procedure. Ink drawdowns on the substrate were produced as ink proofs on the K-proofer. Each ink sample was duplicated four times. Four of each sample were labeled and measured using density and L*a*b* values using spectrodensitometer. The values were averaged and recorded as a baseline. After that, two of each samples were stored in a black bag to prevent exposure to light and stored. The other two were temporarily stored in a black back until they were mounted in the holding rack of the Q-Sun xenon chamber for UV light exposure. The sample location in the chamber was 180^{o} and it was repositioned after every revolution to avoid high concentration of UV light, temperature, and humidity at specific spots. At specific exposure intervals, the samples were measured, density as well as colorimetric values were recorded, and ΔD and ΔE_{00} were calculated using actual and base values.

The amount of the exposure time began with three hour intervals. The time intervals were increased after no different effect showed between each samples. The time was expanded to 8, 10, 15, 24, and 48 hours periodically. (Hyman, M., personal communication, March, 26th, 2017) The procedure was repeated until 230 hours of exposure completed. At the end of the experiment, the two of each sample stored in the black film would be measured again to check the consistency of the inks without exposure.

Data collection. Density and colorimetric values of the two ink sets, standard ink set and High-chroma ink set, were collected during every exposure times. The density and L*a*b* average values of eight samples were collected for each exposure time. ΔD and ΔE_{00} were calculated after collecting the values. The total experiment duration was approximately 230 hours.

Data Analysis

The lightfastness characteristics of the inks were expressed in terms of ΔD and ΔE_{00}. Lower ΔD and ΔE_{00} values mean that ink has a high lightfastness characteristic than higher ΔD and ΔE_{00} values. All values were plotted in a graph showing the relationship between difference and exposure time. Moreover, relationship between ΔD, ΔE_{00}, and % density were plotted to analyze the consistency of ink performance. Lightfastness characteristics of the standard ink set and High-chroma ink set were compared to address the research questions.

The methodology chapter presented the overview of this thesis experiment along with a research steps diagram, equipment, variables, and procedures required to conduct the experiment. Data analysis methodology was also discussed. After conducting this experiment, the results used to conduct analysis to answer the research questions in the final thesis are shown in the following chapter.

Chapter 6

Results

This chapter presents the instrument measurement results in terms of ΔD, ΔL*, Δa*, Δb*, and ΔE_{00} for each ink in the thesis experiment. The data sets are compared between standard and High-chroma inks following the research questions by using a visual analysis of the respective metrics versus the exposure time iterations. The graphs represent correlations of Δ through timed exposure periods ranging from eight to 230 hours.

Pigment Yellow Standard and High-Chroma Results

Pigment yellow consists of Pigment yellow 74, which was rated at BW6, and Pigment yellow 194, which was rated at BW7. The results are presented in graphs comparing standard and High-chroma yellow inks of both Pigment yellow 74 and 194.

ΔD Density results of Pigment yellow. The results are shown in the figures below;

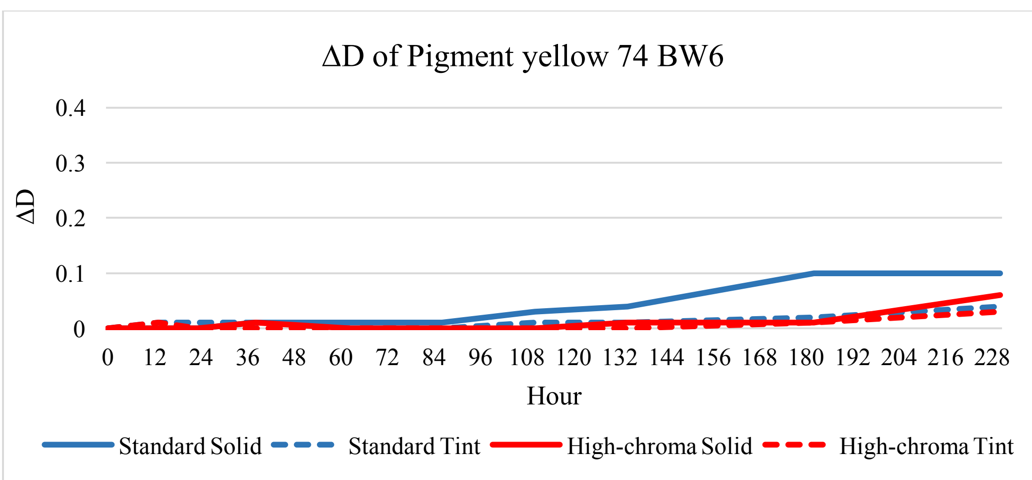

Figure 2. The graph presents ΔD of solids and tints of standard and High-chroma Pigment yellow 74 BW6.

It is important to recognize that small density changes at the beginning of the experiment are considered as instrument noise because of variation that cannot be controlled with the standard instrument. However, at the 110-hour exposure, standard solid of Pigment yellow 74 BW6 started to noticeable decrease in density when compare to the other. The standard solid presented the maximum ΔD of 0.1 at the end of the experiment. As a result, it appeared to fade faster than the solid High-chroma ink. For the tints value, there was no significant difference regarding density between standard and High-chroma inks.

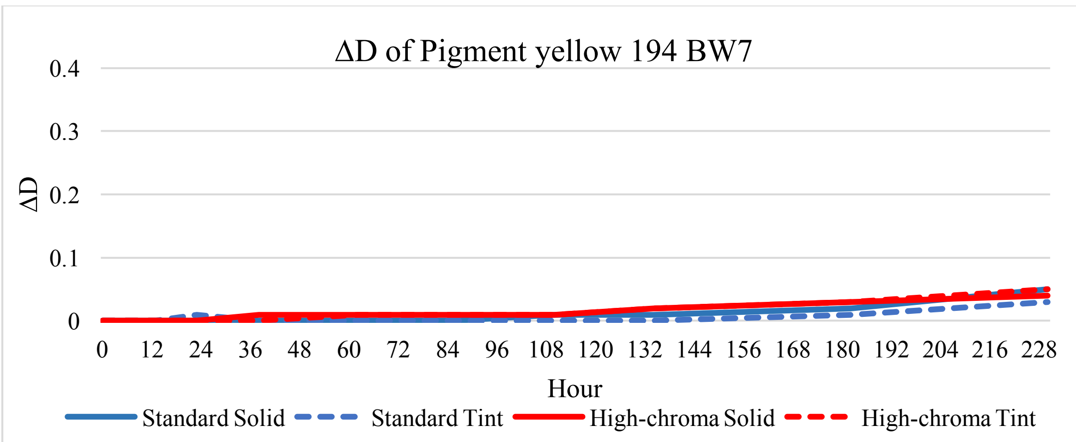

Figure 3. The graph presents ΔD of solids and tints of standard and High-chroma Pigment yellow 194 BW7.

For the Pigment yellow 194 BW7 which exhibited higher BW standard than Pigment yellow 74 BW6, the lightfastness characteristics difference in terms of density between standard and High-chroma inks were similar from the beginning to the end of the experiment.

ΔE_{00} results of Pigment yellow. The results are shown in graphs below:

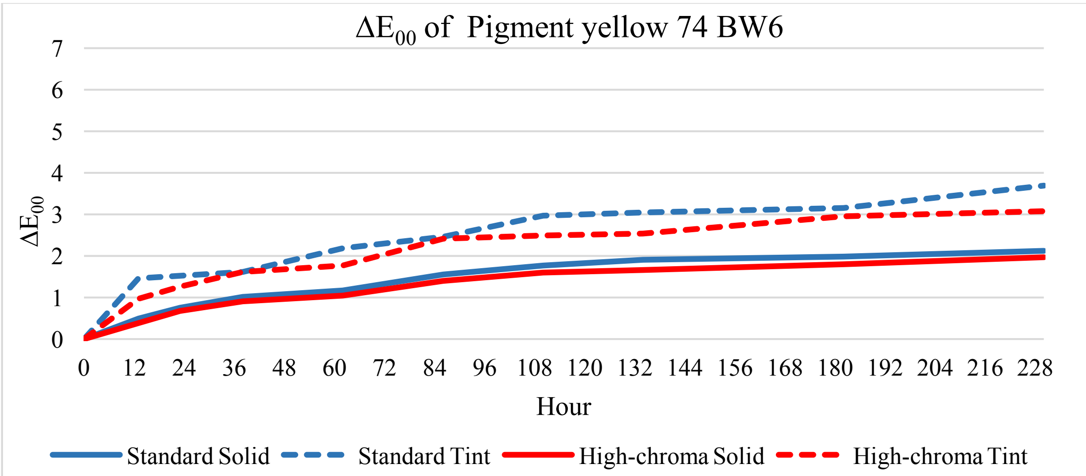

Figure 4. The graph presents ΔE_{00} of solids and tints of standard and High-chroma. Pigment yellow 74 BW6

For the solid Pigment yellow 74 BW6, lightfastness characteristics in terms of ΔE_{00} of standard and High-chroma presented a similar result. They exhibited ΔE_{00} nearly to two at the end of the experiment. On the other hand, tint value of standard inks seemed to fade faster than High-chroma ink. ΔE_{00} value of standard tint was 3.7 and High-chroma was 3.07.

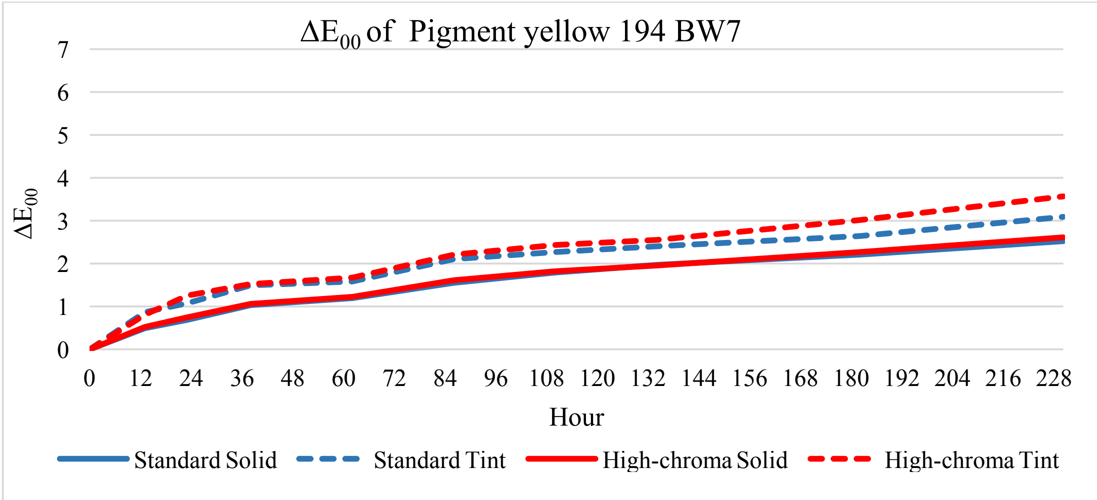

Figure 5. The graph presents ΔE_{00} of solids and tints of standard and High-chroma Pigment yellow 194 BW7.

Likewise, solid Pigment yellow 194 BW7 also exhibited similar ΔE_{00} result that was nearly 2.60 throughout the experiment. At the same time, ΔE_{00} of the tints of both inks exhibited different results. ΔE_{00} value of standard tint was 3.1 and High-chroma was 3.6 at the end of the experiment.

ΔL*, Δa*, and Δb* results of Pigment yellow. The results are shown in the figures below;

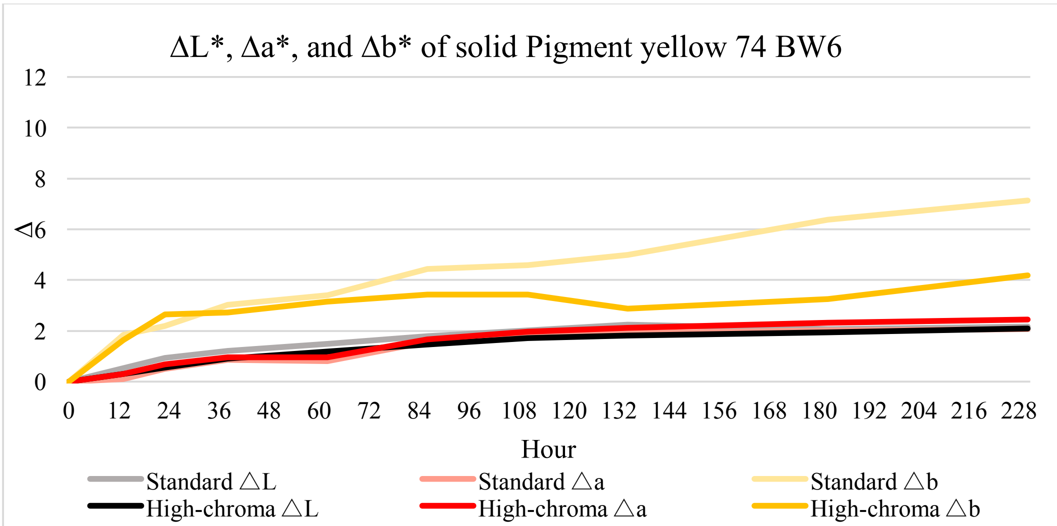

Figure 6. The graph presents ΔL*, Δa*, and Δb* of standard and High-chroma solid Pigment yellow 74 BW6.

There was the most significant difference in change of b* among L*a* and b* values for both standard and High-chroma solid inks. The b* value represents the yellowness to blueness axis. It means that inks shifted in color and became less yellow. For the comparison between standard and High-chroma inks, b* value also exhibited the most different result. Standard ink presented greater b* value shift than High-chroma ink. For the L* which represents lightness, and a* which represents red-green axis, standard and High-chroma showed similar results.

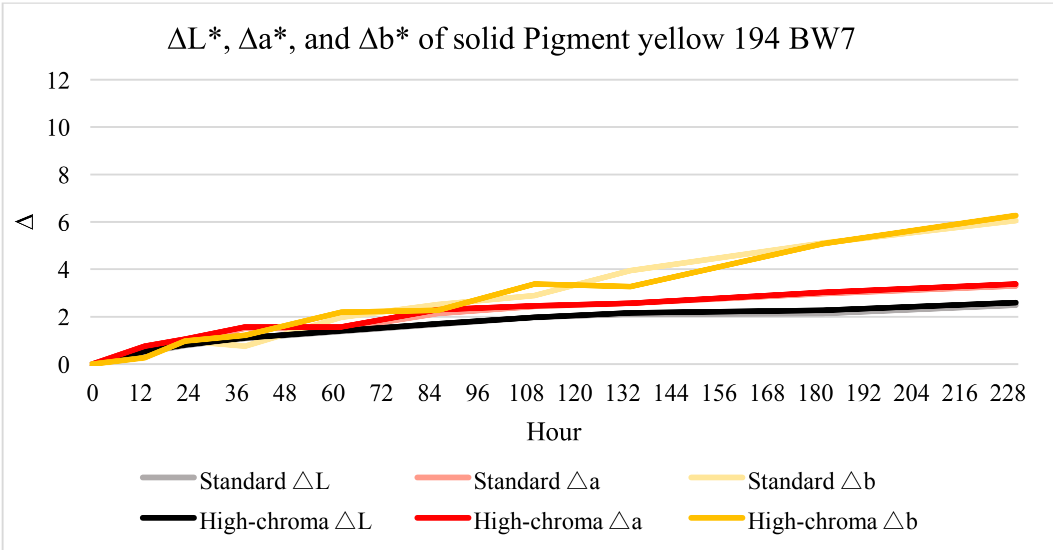

Figure 7. The graph presents ΔL*, Δa*, and Δb* of standard and High-chroma solid Pigment yellow 194 BW7.

For the solid Pigment yellow 194 BW7, the results were similar between standard and high chroma inks, although the Δb* was most dramatically affected by light exposure.

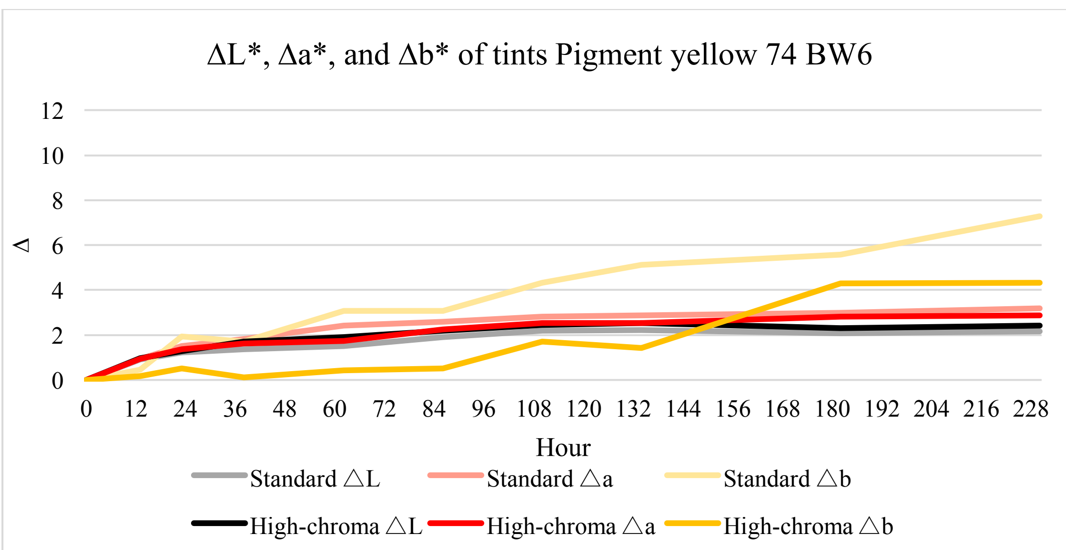

Figure 8. The graph presents ΔL*, Δa*, and Δb* of standard and High-chroma tints Pigment yellow 74 BW6.

For the tint samples, the Δb* value had the most fluctuations in colorimetric values for both standard and High-chroma inks. Δb* of standard and High-chroma exhibited the most varying lightfastness characteristics for ΔL*, Δa*, and Δb* values. Standard ink showed higher Δb* than High-chroma's, which were 7.28 and 4.32, at the end of the experiment.

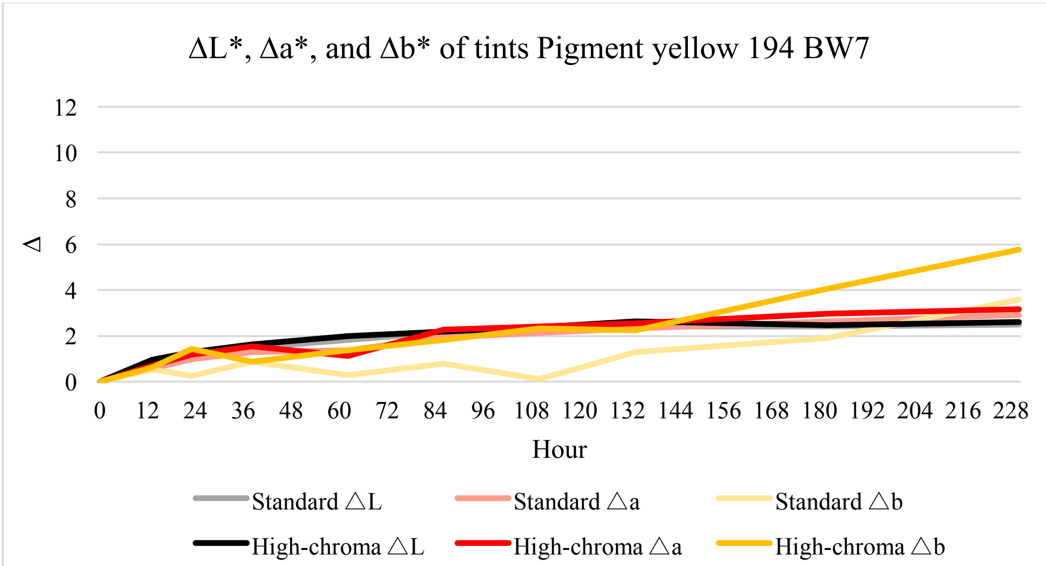

Figure 9. The graph presents ΔL*, Δa*, and Δb* of standard and High-chroma tints Pigment yellow 194 BW7.

Similarly, Δb* of standard and High-chroma exhibited the largest difference. High-chroma ink showed higher Δb* than the standard ink, which were 5.75 and 3.59, at the end of the experiment.

Pigment Magenta Standard and High-Chroma Results

Pigment magenta consists of Pigment red 57:1, which is BW4, and Pigment red 74 which is BW7. The results are presented in graphs comparing between standard magenta and High-chroma magenta ink for Pigment red 57:1 and 74.

ΔD Density results of Pigment magenta. The results are shown in the figures below;

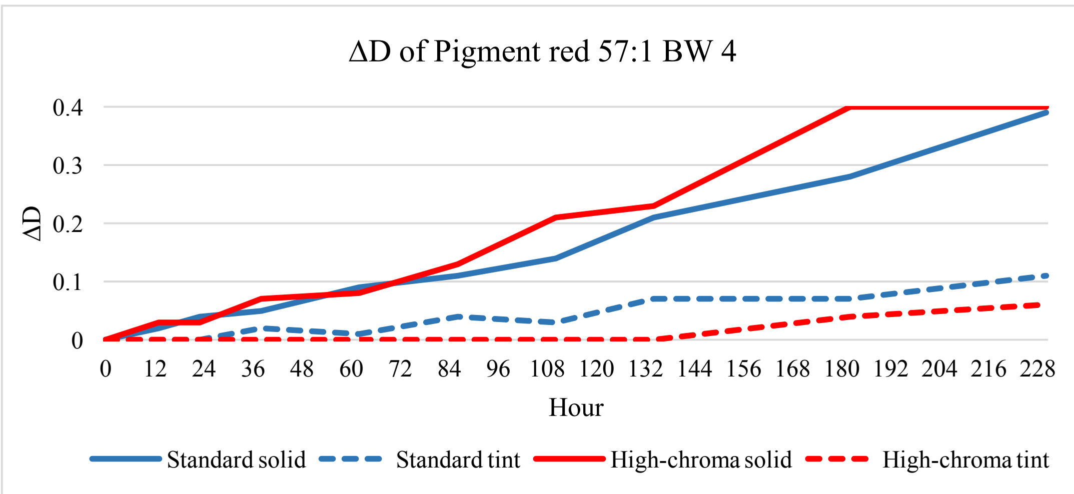

Figure 10. The graph presents ΔD of solids and tints of standard and High-chroma Pigment red 57:1 BW4.

In terms of density, both standard and High-chroma Pigment red 57:1 exhibited similar lightfastness characteristic. Both standard and High-chroma solid presented ΔD at 0.4 and around 0.1 for tint values at the end of the experiment.

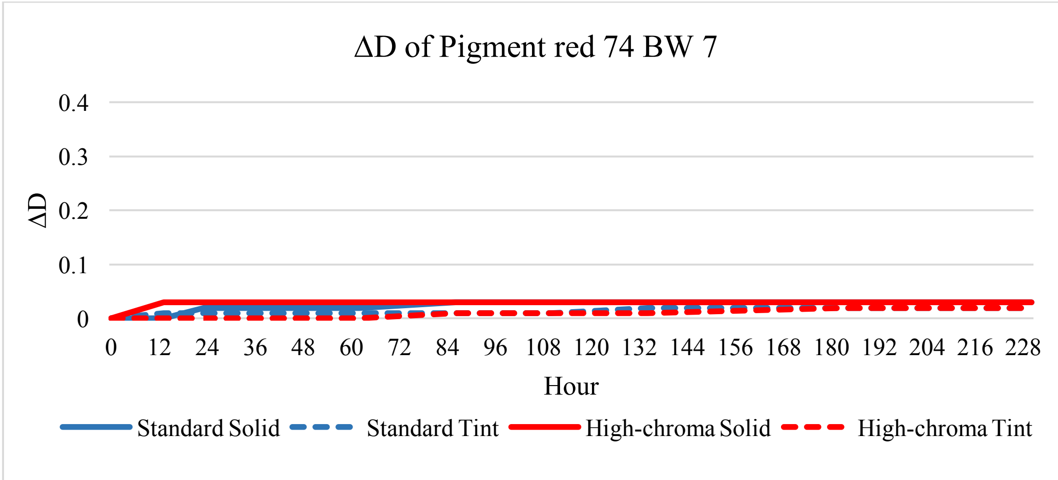

Figure 11. The graph presents ΔD of solids and tints of standard and High-chroma Pigment red 74 BW7.

As a reminder, the magenta inks evaluated were BW4 and BW7 so they were expected to show more dramatic differences in lightfastness characteristics than for the yellows which were BW6 and BW7. Pigment red 74 BW7 presented consistent density throughout the experiment. Although, there was little meaningful difference noted overall between standard and High-chroma inks in terms of density difference for both Pigment red 57:1 and 74.

ΔE_{00} results of Pigment magenta. The results are shown in a graph below:

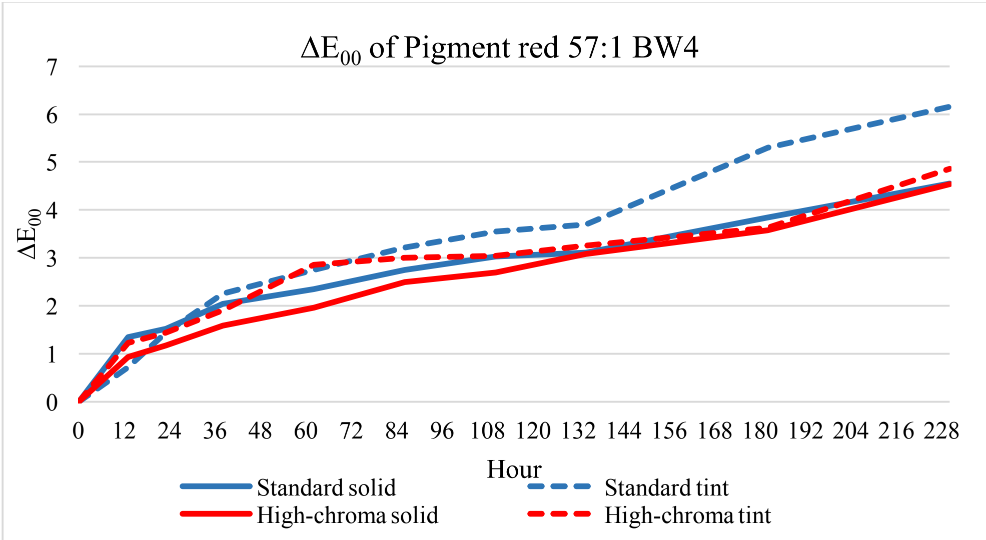

Figure 12. The graph presents ΔE_{00} of solids and tints of standard and High-chroma Pigment red 57:1 BW4.

Solid samples of the standard and High-chroma inks showed the similar result in terms of ΔE_{00}, which was around 4.55. On the other hand, standard Pigment red 57:1 tint gradually exhibited the higher ΔE_{00} than High-chroma ink. The ΔE_{00} of the standard tint at the end of the experiment was 6.16 and the High-chroma tint was 4.86. In consequence, the standard tint seemed to fade quickly than High-chroma tint in terms of colorimetric difference. This comparison showed the most significant evidence of the lightfastness characteristics difference between standard and High-chroma inks.

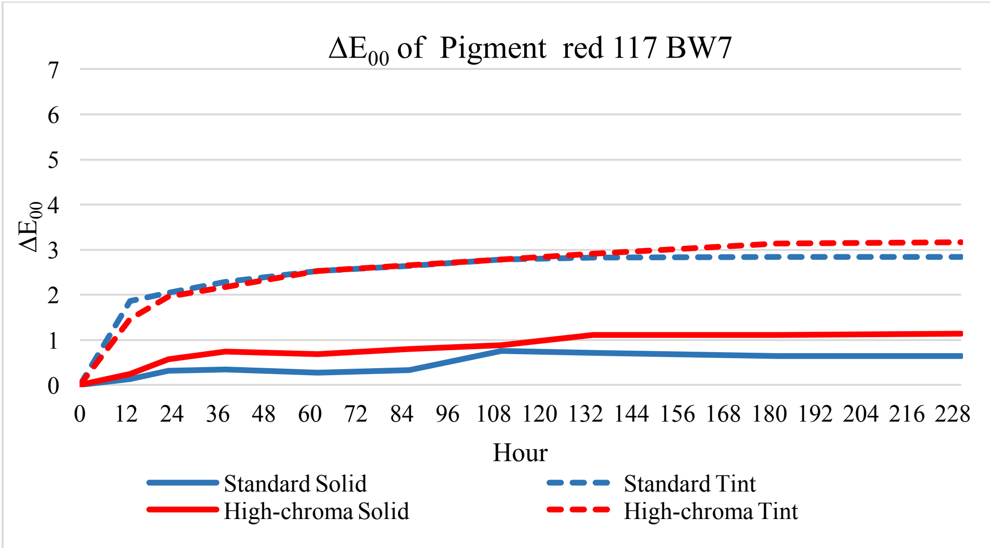

Figure 13. The graph presents ΔE_{00} of solids and tints of standard and High-chroma Pigment red 117 BW7.

For the Pigment red 117 BW7 results, little difference between High-chroma and standard chroma inks was noted. Similar to every ink sets, the tints faded faster than the solids, indicating that process printing color may be more quickly affected than solids.

ΔL*, Δa*, and Δb* results of Pigment magenta. The results are shown in the graphs below;

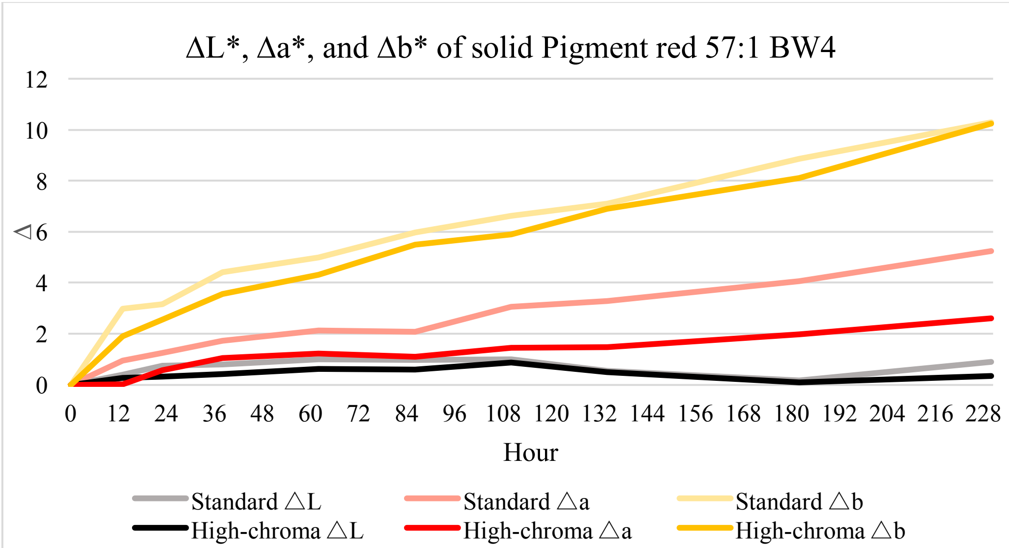

Figure 14. The graph presents ΔL*, Δa*, and Δb* of standard and High-chroma solid Pigment red 57:1 BW4.

In examining the individual L*, a* and b*, the largest difference between standard and High-chroma inks was evidenced in Δa* (the redness to greenness axis), in which the standard ink exhibited a more dramatic change away from redness. Δa* was 5.25 for the standard ink and Δa* was 2.61 for the High-chroma ink at the end of the experiment. Other differences between High-chroma and standard inks were similar, with the most dramatic changes being the b* axis and the inks becoming less chromatic in terms of yellowness.

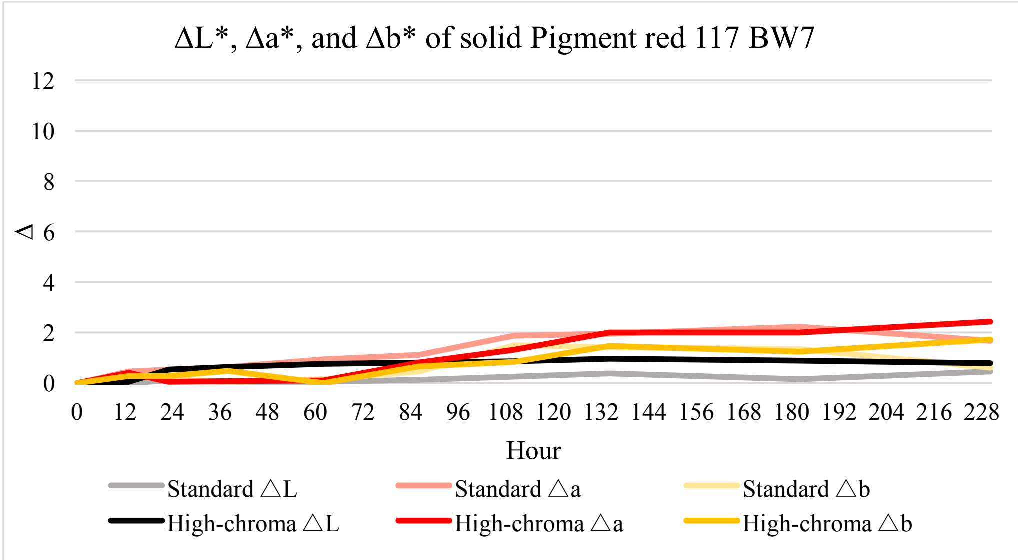

Figure 15. The graph presents ΔL*, Δa*, and Δb* of standard and High-chroma solid Pigment red 117 BW7.

Pigment red 117 BW 7 exhibited better lightfastness characteristics than Pigment red 57:1 BW 4 with little notable difference between the standard and High-chroma inks and colorimetric attributes.

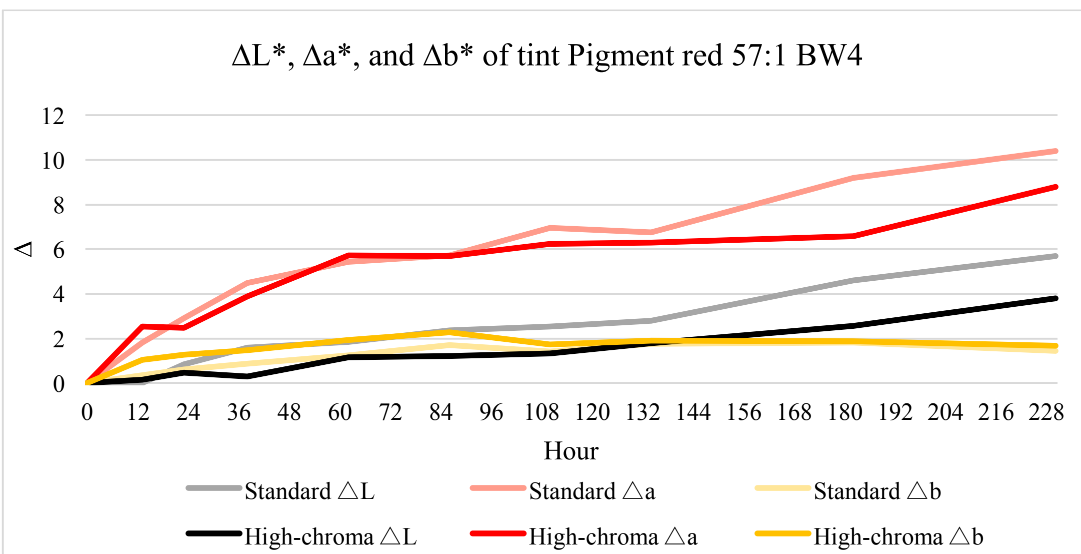

Figure 16. The graph presents ΔL*, Δa*, and Δb* of standard and High-chroma tints Pigment red 57:1 BW4.

Differently, the most dramatic change in colorimetric attributes of the tints Pigment red 57:1 BW 4 was a*, which represented the red-green region for both standard and High-chroma inks. The samples seemed to turn less redness. L* and a* axis exhibited slight differences between standard and High-chroma. Both ΔL* and Δa* values of the standard ink were higher than High-chroma ink at the end of the experiment.

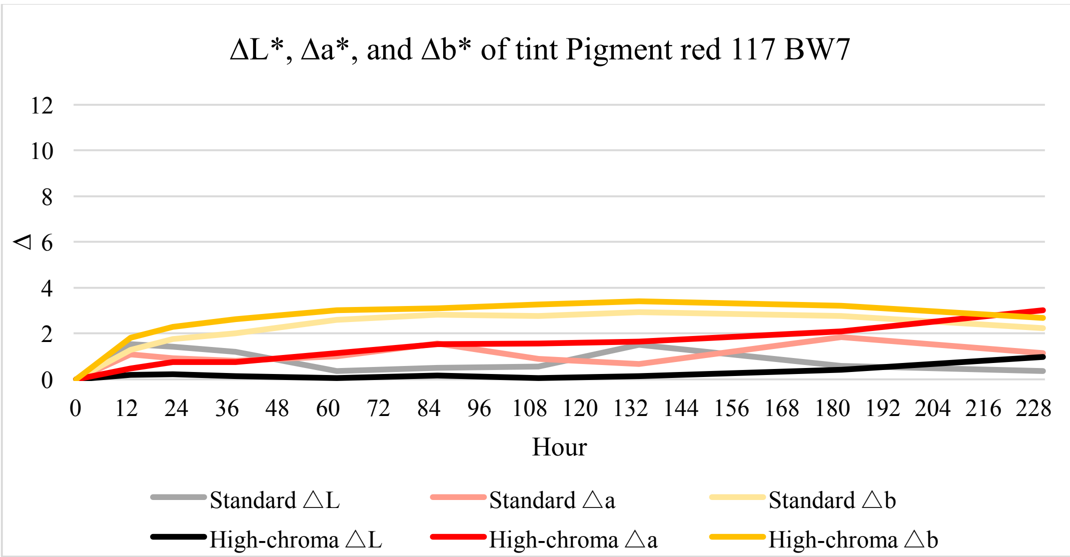

Figure 17. The graph presents ΔL*, Δa*, and Δb* of standard and High-chroma tints Pigment red 117 BW7.

For the tint samples of Pigment red 117 BW7, the standard and High-chroma inks were more stable than Pigment red 57:1. ΔL* and Δb* of both inks were very similar at the end of the experiment. The most significant difference lightfastness characteristics in terms of colorimetric aspects was Δa*.

The Comparison Results Between Yellow and Magenta

The thesis experiment sought not only the lightfastness characteristics difference between standard and High-chroma ink, but also explored the lightfastness characteristics difference between colors. After getting the results of yellow and magenta inks, the researcher compared the data sets to answer the research questions. The pigments that researcher used to examine were the Pigment yellow 194 and the Pigment red 117 which have similar BW standard of 7. The standard Pigment yellow and red were compared along with High-chroma pigments.

ΔD results of Pigment yellow and magenta. The results are shown in the graph below;

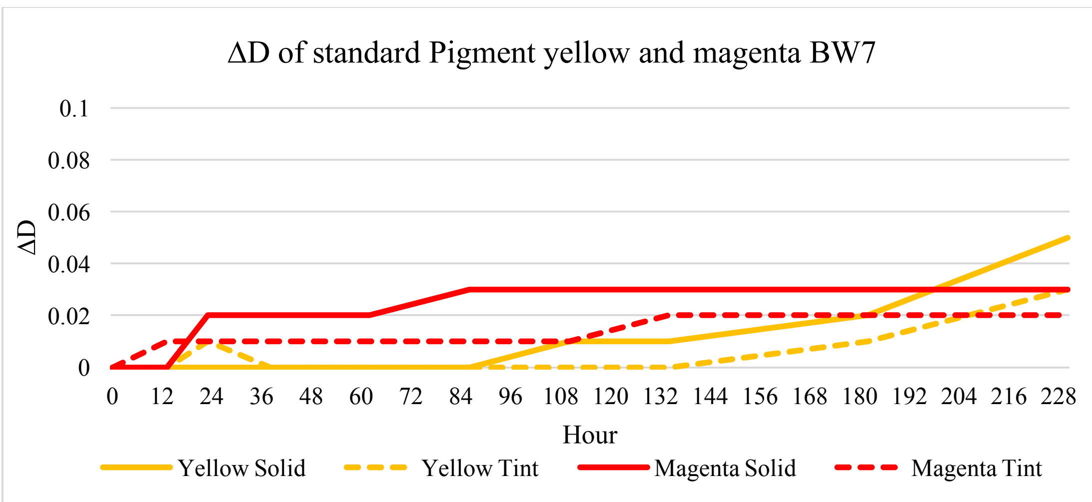

Figure 18. The graph presents ΔD of standard Pigment yellow 194 and Pigment red 117 BW7.

The Pigment red started to lose its density at the 13-hour exposure. On the other hand, Pigment yellow was more stable from the beginning, but began to lose its density at 86-hour exposure. ΔD of Pigment yellow surpassed Pigment red and presented less lightfastness at the end of the experiment. However, the difference in ΔD of Pigment yellow and red was meager as the difference in ΔD of solids was 0.02 and tints was 0.01.

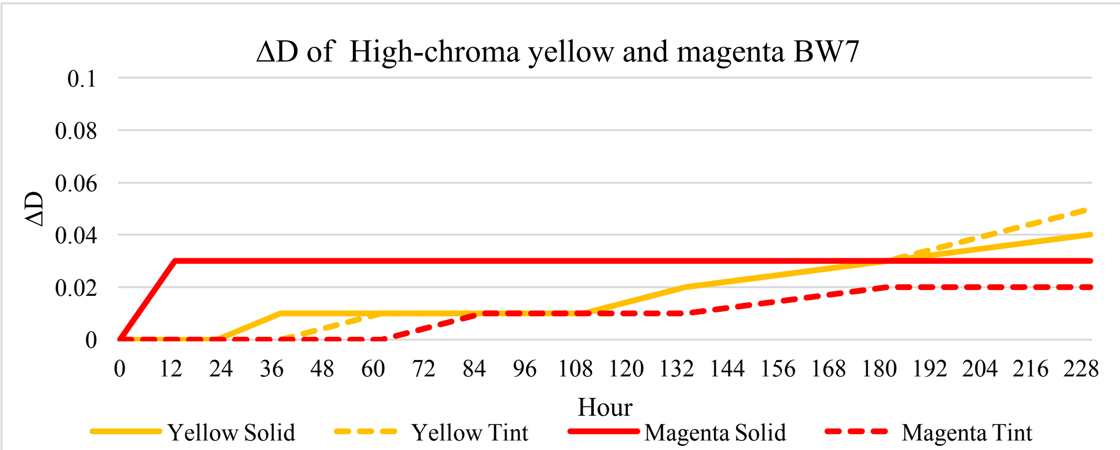

Figure 19. The graph presents ΔD of High-chroma Pigment yellow 194 and Pigment red 117 BW7.

In comparison to the High-chroma ink, solid Pigment red 117 changed its density after the first 13 hours. Tint value was a bit more stable at the beginning and slowly shifted in density. Pigment yellow 194 seemed to be more stable at the beginning, but at the end of the experiment both solid and tint yellow ΔD surpassed Pigment red similarly to standard inks.

ΔE_{00} results of Pigment yellow and magenta. The results are demonstrated in the figures below;

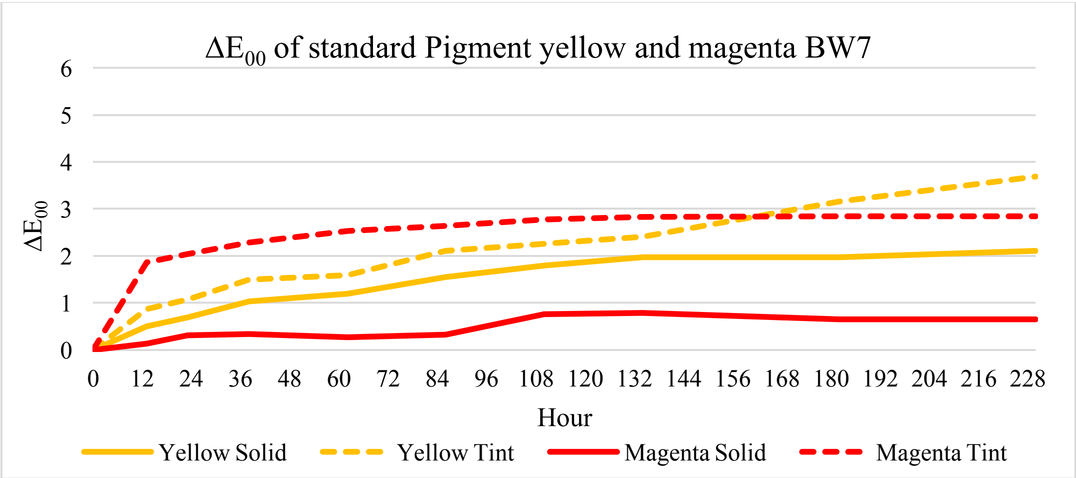

Figure 20. The graph presents ΔE_{00} of standard Pigment yellow 194 and Pigment red 117 BW7.

For the ΔE_{00}, standard yellow tint faded less quickly than the magenta tint, but surpassed the magenta near 160 hours and continued to fade where the magenta ink plateaued near 100 hours. Both solid and tint standard Pigment yellow had faded more than Pigment red at the end of the experiment.

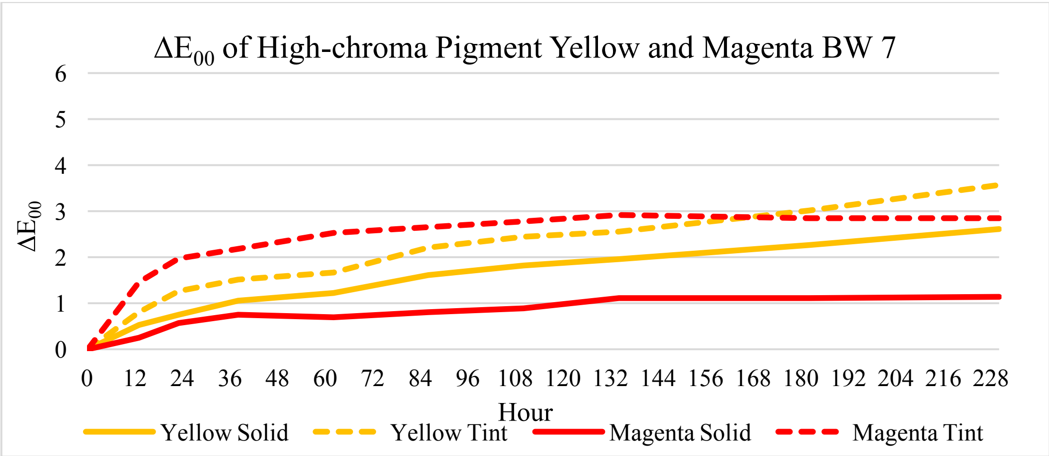

Figure 21. The graph presents ΔE_{00} of High-chroma Pigment yellow 194 and Pigment red 117 BW 7.

Similar results were obtained with the High-chroma ink sets. Tint Pigment red faded faster at the beginning. Tint Pigment yellow surpassed Pigment red after the 160-hour exposure and showed the lower lightfastness results for both solid and tint at the end of the experiment.

ΔL*, Δa*, and Δb* results of Pigment magenta. The results are presented in the figures below;

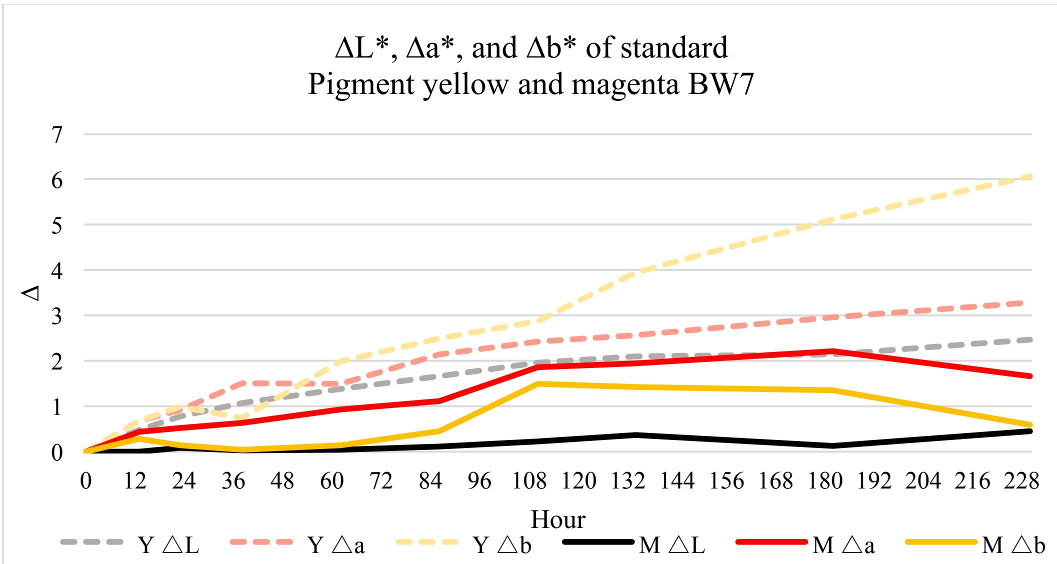

Figure 22. The graph presents ΔL*, Δa*, and Δb* of solid standard Pigment yellow 194 and Pigment red 117 BW7.

Considering at ΔL*, Δa*, and Δb* values, the standard Pigment yellow shifted in color more than the standard Pigment red for all values. Pigment yellow shifted in blue-yellow axis especially in b* region and turned to be less yellow at the end of the experiment.

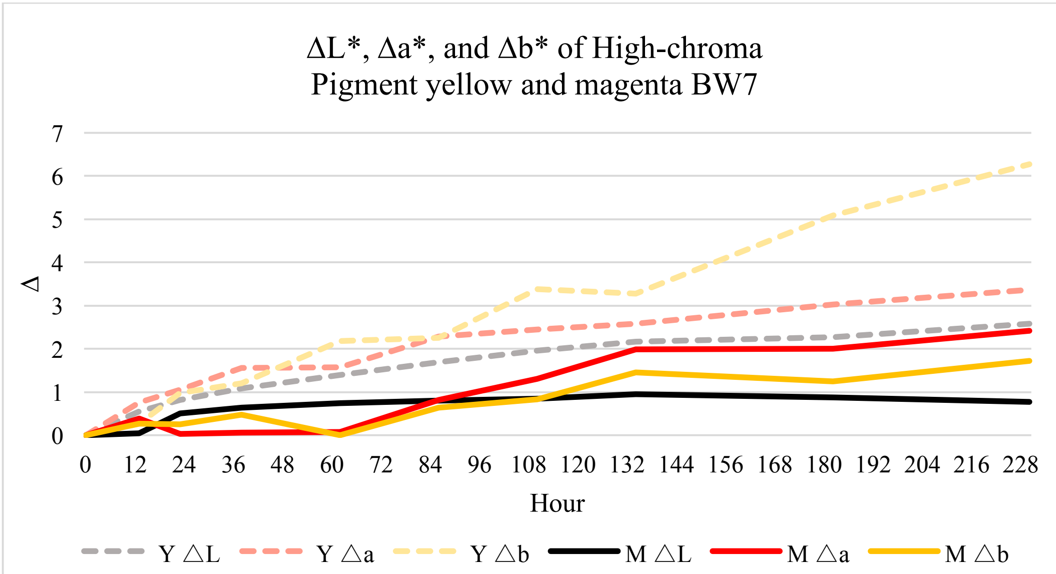

Figure 23. The graph presents ΔL*, Δa*, and Δb* of solid High-chroma Pigment yellow 194 and Pigment red 117 BW7.

Similarly, High-chroma Pigment yellow exhibited color shift more than Pigment red for all values. The biggest shift value was Δb*.

The next chapter will review this data to offer summaries and conclusions in reference to the previously outlined research questions.

Chapter 7

Summary and Conclusion

The results of the study presented significant information that can be summarized to answer each of the following research question. This chapter will lead to the conclusion of the experiment and offer suggestions for future research projects.

Research Question 1: Is there a difference in the lightfastness characteristics of the solids of process magenta and yellow ink sets between standard and High-chroma inks?

The results of the experiment are answered by comparing ΔD, ΔL^*, Δa^*, Δb^*, and ΔE_{00} each set of ink shown in the following table.

Table 4
Summary of research question one

	Comparison sets		Condition	Comparison values	Summary
RQ 1.1	Yellow standard ink	Yellow High-chroma ink	Solid	ΔD	Standard BW6 seemed to fade faster
RQ 1.2	Yellow standard ink	Yellow High-chroma ink		ΔL^*, Δa^*, Δb^*, and ΔE_{00}	No significant difference
RQ 1.3	Magenta standard ink	Magenta High-chroma ink		ΔD	No significant difference
RQ 1.4	Magenta standard ink	Magenta High-chroma ink		ΔL^*, Δa^*, Δb^*, and ΔE_{00}	No significant difference

From Table 4, research question one sought to find the difference in lightfastness characteristics of the standard and High-chroma solid Pigment yellow. Two BW scale pigments were investigated and the details are described below.

RQ.1.1. There were different lightfastness characteristics in terms of density for the standard and High-chroma solid Pigment yellow 74 BW6 ink. The result showed that standard ink lost its density more than High-chroma ink and seemed to fade more than High-chroma ink. On the other hand, the standard and High-chroma solid Pigment yellow 194 BW7 had an insignificant difference of a very low value in ΔD. BW7 is an excellent lightfastness standard.

RQ.1.2. For the colorimetric difference, ΔE_{00} of the standard and High-chroma for both solid Pigment yellow 74 and 194 had no significant difference. Even though the Δb^* result of solid Pigment yellow 74 BW6 shifted higher than the High-chroma ink, it indicated that the standard solid Pigment yellow 74 BW6 was only somewhat less yellow than the High-chroma ink after 200 hours (0.6 ΔE_{00}).

RQ.1.3. There were indifferent lightfastness characteristics in terms of density between standard and High-chroma solid Pigment red 57:1 BW4 and 74 BW7. BW4 inks shift similarly whereas BW7 inks were mostly stable in density.

RQ.1.4. Similar to yellow ink sets, magenta solid inks had insignificant lightfastness characteristics between standard and High-chroma for Pigment red 57:1 BW4 and 117 BW7.

Research Question 2. Is there a difference in the lightfastness characteristics of the tints of process magenta and yellow ink sets between standard and High-chroma inks?

The summary of research question two is shown in the table below;

Table 5
Summary of research question two

	Comparison sets		Condition	Comparison values	Summary
RQ 2.1	Yellow standard ink	Yellow High-chroma ink	Tint	ΔD	No significant difference
RQ 2.2	Yellow standard ink	Yellow High-chroma ink		ΔL*, Δa*, Δb*, and ΔE_{00}	No significant difference
RQ 2.3	Magenta standard ink	Magenta High-chroma ink		ΔD	No significant difference
RQ 2.4	Magenta standard ink	Magenta High-chroma ink		ΔL*, Δa*, Δb*, and ΔE_{00}	Standard BW4 seemed to fade faster (ΔE_{00} diff = 1)

From Table 5, research question two is summarized using similar comparison sets as research question one, but with the tint condition considered. Tints provided less ink coverage area and represented lower density. Thus, the researcher expected to perceive different results from research question one and the details are described in the following.

RQ.2.1. There were no significant lightfastness characteristics difference in terms of density between standard and High-chroma inks for both tint Pigment yellow 74 BW6 and 194 BW7. Both pigments lost their density less than 0.05.

RQ.2.2. There were no significant lightfastness characteristics difference in terms of colorimetric values between standard and High-chroma inks for both tint Pigment yellow 74 BW6 and 194 BW7.

RQ.2.3. There were no significant lightfastness characteristics difference in terms of density between standard and High-chroma tint Pigment red 57:1 BW4 and 74 BW7. However, standard ink for Pigment red 57:1 BW4 showed a small shift in density more than the High-chroma ink at the end of the experiment.

RQ.2.4. There were notable lightfastness differences in terms of colorimetric values for Pigment red 57:1 BW4. The shifts of tint standard Pigment red 57:1 equaling $\Delta E_{00} = 1$ were far off from the other samples. As mentioned in the literature, $\Delta E_{00} = 1$ shown in the result means the color obviously shifted for the trained eye.

Research Question 3. Is there a difference in the lightfastness characteristics between yellow and magenta standard inks?

This research question compared pigment yellow and magenta using Pigment yellow 194 and Pigment red 117, which had the similar BW standard of seven. The summary of research question three is shown in Table 6.

Table 6

Summary of research question three

	Comparison sets		Comparison values	Summary
RQ 3.1	Yellow standard ink	Magenta standard ink	ΔD	Magenta seemed to have better lightfastness
RQ 3.2	Yellow standard ink	Magenta standard ink	ΔL^*, Δa^*, Δb^*, and ΔE_{00}	Magenta seemed to have better lightfastness

For the standard yellow and magenta ink sets, there were small different lightfastness characteristics. Magenta ink started to fade earlier than yellow ink at the beginning, but it seemed to be more stable than yellow ink and presented less ΔD and ΔE_{00} at the end of the experiment.

Moreover, Pigment yellow exhibited bigger colorimetric attributes changes especially for the b* axis which is the blue-yellow region. Pigment yellow seemed to fade more for both solid and tint standard inks.

Research Question 4. Is there a difference in the lightfastness characteristics between magenta and yellow High-chroma inks?

Table 7

Summary of research question four

	Comparison sets		Comparison values	Summary
RQ 4.1	Yellow High-chroma ink	Magenta High-chroma ink	ΔD	Magenta seemed to have better lightfastness
RQ 4.2	Yellow High-chroma ink	Magenta High-chroma ink	ΔL^*, Δa^*, Δb^*, and ΔE_{00}	Magenta seemed to have better lightfastness

Similar to the standard inks, there were small different lightfastness characteristics between High-chroma yellow and magenta inks. Yellow seemed to have better lightfastness characteristics at the beginning, but magenta ink was more stable and presented better lightfastness characteristics at the end of the experiment. However, High-chroma yellow and magenta inks showed less lightfastness difference than standard yellow and magenta inks.

Conclusions

There were significant differences in lightfastness characteristics regarding colorimetric attributes between standard and High-chroma inks for the tint samples with lower a BW standard. The High-chroma inks seemed to have higher lightfastness than the standard inks. For the higher BW standard inks, the researcher could not identify a significant difference between standard and High-chroma inks. Moreover, as expected, higher BW rating inks presented higher lightfastness characteristics and solid samples showed better lightfastness characteristics than tint samples. This result was demonstrated clearly in the tint samples of the tint Pigment red 74 BW4. The lightfastness of tint and solid results also supported the literature that inks with higher density have better lightfastness characteristics.

From visual inspection, the standard inks seemed to fade consistently after light exposure and visually exhibited a smoother ink film than the High-chroma inks. High-chroma samples revealed small cracks on the surface, especially for Pigment red 117 BW7. Therefore, for the practical purpose, it is recognized that although High-chroma ink can produce expanded gamut printing, but other factors may influence the performance of the ink in a production setting. Experts indicate that press latitude may be sacrificed with High-chroma ink (Roth, J., personal communication, October 19th, 2017).

Limitations and Future Research

The primary limitation of the study is the time interval for the experiment. Unlike the outdoor light exposure conditions, indoor light exposure conditions provide less light damage and less photo-degradation to surfaces. Some comparison results were not clearly distinguished such as lightfastness characteristics between ink sets especially for the high BW rating ink. Moreover, there is no relevant literature about correlation between lightfastness standard and indoor light exposure conditions. Consequently, the researcher could not specify sufficient time intervals from the beginning of the experiment.

Another limitation is the size and numbers of samples. The researcher needed to limit size and number of samples due to the specific dimension of Q-sun xenon chamber at PAL. More examples with the larger surface area would provide more accurate results regarding statistics because printing samples in general are not produced equally smooth throughout the surfaces.

In future research, they are several issues that can be examined further, the most prominent of which are listed below.

1. Time intervals could be expanded longer than the 230-hour exposure. The researchers would see the results more clearly than this thesis experiment. Moreover, the results may change due to the longer time exposure. The best example of this case is the results of research question three and four. At the beginning, magenta inks seemed to fade more quickly than yellow, but magenta inks presented better lightfastness characteristics than yellow inks at the end of the experiment.

2. Future researcher could adapt L*C*h° color space to investigate lightfastness characteristics during analysis. This research showed that inks generally fade from brighter to duller. ΔC* would distinctly identify the color difference in chroma.
3. The purpose of this thesis is for package printing which has a variety of substrates. Future experiments using different substrates for packaging such as plastic film may exhibit different results.
4. Future researchers could study lightfastness characteristics of high BW rating and High-chroma inks in terms of surface quality and press latitude after light exposure.

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Appendix I

standard and High-chroma inks data collection sheet

Exposure Time	Density	Standard water-based flexographic inks															
		Magenta								Yellow							
		PR57:1				PR177				PY74				PY194			
		Density	ΔD	L*a*b*	ΔE_{00}	Density	ΔD	L*a*b*	ΔE_{00}	Density	ΔD	L*a*b*	ΔE_{00}	Density	ΔD	L*a*b*	ΔE_{00}
Initial	100%																
	45%																
8 hours	100%																
	45%																
X hours	100%																
	45%																

Exposure Time	Density	High-Chroma water-based flexographic inks															
		Magenta								Yellow							
		PR57:1				PR177				PY74				PY194			
		Density	ΔD	L*a*b*	ΔE_{00}	Density	ΔD	L*a*b*	ΔE_{00}	Density	ΔD	L*a*b*	ΔE_{00}	Density	ΔD	L*a*b*	ΔE_{00}
Initial	100%																
	45%																
8 hours	100%																
	45%																
X hours	100%																
	45%																