8-2021

Lightfastness of Water-based Inks vs. Latex Water-based Inks

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Recommended Citation

Lopez Lopez, David, "Lightfastness of Water-based Inks vs. Latex Water-based Inks" (2021). Thesis. Rochester Institute of Technology. Accessed from

Lightfastness of Water-based Inks vs. Latex Water-based Inks

by David López López

A Thesis submitted in partial fulfillment of the requirements

for the degree of Master of Science in Print Media in the

Department of Graphic Media Science and Technology

in the College of Engineering Technology of the

Rochester Institute of Technology

August 2021

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Rochester, New York

Certificate of Approval

Lightfastness of Water-based Inks vs. Latex Water-based Inks

This is to certify that the Master's Thesis of
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Acknowledgments

I would like to express my deepest gratitude to my advisor, Dr. Gregory S. D'Amico, whose sincerity and encouragement I will never forget. Dr. D'Amico has been an invaluable guide as I hurdled through the path of this Masters degree. I would also like to thank Dr. Birkett for her significant input. This thesis would not have been possible without Dr. Myers, whose insight and expertise in color science helped shape this research. I would also like to thank the Printing Applications Lab at Rochester Institute of Technology for allowing me to use all the equipment needed and for guiding me through the experimentation process. Finally, I am grateful for my parents whose constant love and support keep me motivated and confident. My accomplishments and success are because they believed in me.

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Abstract

This study focused on the lightfastness properties of non-latex water-based inkjet inks and latex inkjet inks for conventional process colors, i.e., cyan, magenta, yellow, and black. Lightfastness is defined as the property of ink that describes the degree of resistance to fading when exposed to light. Lightfastness varies among inks based on their formulation. The degradation of inks caused by light happens when the light is absorbed by the pigments and reacts with the pigments and molecules in the printed substrate. This research evaluated the lightfastness degree of water-based inkjet inks vs. latex inkjet inks. The experiment used printed samples subjected to equal amounts of light, using established methodologies for accelerated aging. The data gathered from the prints included information on color shift as expressed by L*a*b* and $\Delta E_{00.}$ Data analysis was performed to compare the before and after exposures of the two types of ink. It was concluded that the latex inkjet ink formulation improved the lightfastness properties when compared to water-based inkjet inks, particularly with magenta and cyan.

Chapter 1

Introduction

From newspapers to food packaging, from magazines to roadside advertising, the world is replete with printed materials. The process of printing involves the reproduction of a pattern on a substrate, usually in the form of text, images, or, in many cases, both (Calvert, 2001). Printed material uses text and images to communicate various ideas, memories, and events. The printing processes involve different technologies that result in varying formats, quality, speed, and print longevity.

Conventional printing technologies, including lithography, flexography, gravure, and screen printing, have evolved and are currently capable of producing high-quality prints at low cost. These conventional printing technologies share one specific feature: the image to be printed is located physically in the device and is embedded on a roller, a plate, or a screen and is transferred by direct or indirect contact to the substrate. The printed image is formed by a pattern that has been defined well before the press starts running. Changes to the image can be achieved by making physical modifications to the image embedded on the roller or other device.

Inkjet Printing

Inkjet printing, on the other hand, uses a different principle. Not having a pre-established pattern mounted in the press, this technology progressively builds the pattern directly on the substrate by depositing a large number of individual drops of ink.

Today’s global printing industry represents a significant area of economic activity and exceeds US $1 trillion (*IBISWorld - Industry Market Research, Reports, and Statistics*, 2020). Over the past decade, inkjet technology has increased its activity in the market, and it is expected to grow even more. The main reason for this is that the patterns are always represented as digital data files and are never embedded into a physical object before printing, thus allowing the patterns to be changed faster, lowering setup costs and times (Hoath, 2016).

As the inkjet printing industry grows, this technology is used for more applications, and its development and evolution continue. The capability of this relatively new printing method to overcome certain limitations of conventional printing technologies defines the digital era. Longevity is an essential attribute in many applications for printed media, and water-based inkjet is no exception here. One of the several factors that define the longevity of printed material is lightfastness, the resistance of prints to light-induced fading. The digital printing industry as a whole has struggled to match the lightfastness that some of the conventional printing technologies can provide (Rasmusson, Chovancova, Fleming & Pekarovicova, 2005).

The inkjet printing technology sector has tried to improve the limitations of lightfastness by developing new ink formulations. For example, latex inkjet ink is a formulation that uses latex as an additive polymer in water-based inkjet ink. This formulation consists of a liquid ink vehicle that contains this polymer that encapsulates the pigment, acting as an extra layer of protection and lowering the effects of daylight on a printed image (Yang & Naarani, 2007).

Problem Statement

This research aimed to determine the lightfastness of latex inkjet ink and compared it to regular water-based inkjet ink by using an established accelerated method of light exposure. Previously documented data and methods were used as a basis for this research.

Purpose of the Study

The purpose of this study was to determine the difference in lightfastness degree of inkjet inks formulated with latex as an additive compared to water-based inkjet inks by measuring the effect of accelerated light exposure on individual process colors. The independent variable in this study was the time the samples were exposed to light inside the weathering chamber. Held as control variables were: the temperature inside the weathering chamber; the time of exposure; the humidity in the chamber; the substrate; and the inks used in each sample. Samples were measured using a single X-Rite eXact spectrodensitometer. The dependent variable was the change in color, as expressed by CIE ΔL^*, Δa^*, and Δb^* as well as ΔE_{00} as an expression of overall color difference. Both the image areas and the non-image area were measured.

Chapter 2

Theoretical Basis

The present chapter outlines the key concepts and theories relevant to the topic, whereas previous research on the subject is presented in the subsequent chapter comprising a literature review. This study utilizes a straightforward experiment testing the lightfastness of printing inks. Its theoretical basis rests in the scientific method of experimental inquiry. After a brief commentary on the scientific method, the standards on the quantification of lightfastness degree are discussed.

Scientific Method

The study is hypothetical-deductive, with roots established in the scientific method, which begins with concepts not derived from experience in the world that is "out there" but instead are postulated in the form of hypotheses by researchers through their intuition. In addition to generating such possible conjectures about reality, scientists test them, that is, confront them in nature through observations or experiments. In this method, induction plays no role; in fact, it is consciously avoided. The hypothetical-deductive method postulates that the researcher investigates the nature of the study, well-equipped with ideas about what the individual seeks to find, carrying a preliminary concept of reality. Thus, the researcher starts with problems that arise from discrepancies between expectations and reality. According to Creswell (2013), science begins at the time when the hypothetically anticipated structure of a segment of nature does not correspond to it.

Quantification of Color

The perception and interpretation of color are subjective, for each observer interprets color based on personal impressions. In addition, eye fatigue, age, the environment in which one views color, and other factors can influence color perception (Momsen, 2005). This means that each person also communicates color perception of an object in a unique way, limiting how objective a person can be in communicating a color to another person, thus creating the need for a type of standard that assigns a numeric value to colors.

Munsell Scale

Professor Albert H. Munsell created the Munsell color system in the early 1900s as a precise way to specify and display the relationships among colors. Munsell noted three attributes to describe color, which he termed hue, value, and chroma[1]. Munsell created numerical scales that attempted to show the colors separated by visually equal spaces. That is not too difficult to do for a range of grays ranging from white to black.

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[1] While hue and chroma are commonly used terms today, the attribute that Munsell described as value is more commonly referred to as lightness (Berns et al., 2019). Berns (2019) cites CIE 17.4 and ASTM E284 provides the following definitions: "Hue: Attribute of a visual perception according to which an area appears to be similar to one of the colors, red, yellow, green, and blue, or to a combination of adjacent pairs of these colors considered in a closed ring (CIE, 2020b). Lightness: Attribute by which a perceived color is judged to be equivalent to one of a series of grays ranging from black to white (E12 Committee, 2017). Chroma: Attribute of color used to indicate the degree of departure of the color from gray of the same lightness (E12 Committee, 2017)".

One simply needs to analyze the results obtained from the input of a considerable number of observers. The Munsell System of Color Notation is significant from a historical perspective because it is based on human perception.

Moreover, it was devised before instrumentation was available for measuring and specifying color. The Munsell System assigns numerical values to the three properties of color: hue, value, and chroma. Adjacent color samples represent equal intervals of visual perception (Momsen, 2005).

CIE Standard Colorimetric System

The Commission Internationale de I'Eclairage (CIE) color system is the most widely known as a mathematical representation and system to quantify color. Based on the findings of Munsell, the CIE sought to standardize color measurement so it could be used for industrial purposes (CIE, 2020a).

The CIE developed systems for converting spectral data, which can be effectively used by industry for specification and comparison purposes. These systems are based upon human vision as defined by the standard observers (1931 and 1964) and the spectral reflection of the object that is measured. These are manifested in the resultant tristimulus values (X, Y, and Z) and the trichromatic coefficients (x, y, and z) and are often displayed graphically in the CIE chromaticity diagram commonly known as the xyY chromaticity diagram. Due to limitations in the CIE chromaticity diagram, notably that equal distances do not represent equal visual differences, and two samples of the same chromaticity (x, y) and different luminance (Y) will not appear equally saturated, points on the CIE chromaticity diagram "…often give misleading impressions of the colors of the samples they represent and of the color differences between two samples" (Bruno, 1986 p.325). As a result, subsequent color systems were derived from the three tristimulus values in the CIE system, the most popular of which is CIELAB.

CIE L*a*b* Color System

There are two undeniable problems in specifying colors in terms of tri-stimulus and chromaticity values:

1. This specification of colors is not easily interpreted in terms of the psychophysical dimensions of color perception, namely lightness, chroma, and hue.
2. The XYZ system and associated chromaticity diagrams are not perceptually uniform.

A recognized limitation of the XYZ system and associated chromaticity diagrams is that it is difficult to calculate the differences between two color stimuli (Choudhury, 2014).

In response to these and other limitations, the CIE 1976 L*, a*, b* space was introduced, with the official abbreviation CIELAB (Berns et al., 2019). In those cases, in which a*=b*=0 is achromatic, the L* axis represents the achromatic scale of grays ranging from white to black. The proportions of L*, a*, and b* are obtained from the tri-stimulus values according to the transformations shown in Equations 1, 2, and 3, where Xn, Yn, Zn are the values for the reference white that the observer is using.

$$L^{*} = 116f\left(\frac{Y}{N_n}\right)^{\frac{1}{3}} - 16 \qquad (1)$$

$$a^{*} = 500\left\lfloor f(X - X_n)^{\frac{1}{3}} - f\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}}\right\rfloor \qquad (2)$$

$$b^{*} = 200\left\lfloor f\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - f\left(\frac{Z}{Z_n}\right)^{\frac{1}{3}}\right\rfloor \qquad (3)$$

Lightfastness

The theoretical basis of this study now examines lightfastness, its standards, and testing. Lightfastness is recognized as one of the main limitations of new printing technologies and one of the most important and demanded product features (Wilhelm, 2002).

Lightfastness refers to the resistance of color to fading under the sunlight (Zeller-Gmelin Corporation, 2017). Sunlight is part of the electromagnetic spectrum; the part of the spectrum in which daylight is present ranges from 380 to 760 nanometers. Present in the lower side of the daylight range is ultraviolet light; these waves can present themselves from 100 to 300 nanometers and are known to be responsible for most of the color fading in printed material (Calvert, 2001).

There are different types of ultraviolet wavelengths; they are divided into UV-A, UV-B, and UV-C. According to the World Health Organization, UV-B is the second most damaging group of wavelengths affecting human DNA. The same characteristic that causes skin cancer is also responsible for the fading of color even though these waves are filtered by the atmosphere (Lucas, 2001). In order to understand how color fading by UV light occurs in an ink sample, it is crucial to know the chemical makeup of the ink. In the present study, all the chemical ink formulations were aqueous formulations containing soluble dyes and pigments.

Witt (as cited in Maccoll, 1947) postulated in 1876 that color is present in a compound due to the presence of groups called chromophores (Maccoll, 1947). Present in the chemical composition of the ink, chromophores behave as light-absorbing bodies and are part of the chemical bonds that will ultimately be affected by the UV wavelengths. The degradation of inks caused by ultraviolet wavelengths happens when the light is absorbed by the pigments and dyes, which later reacts with them by breaking the chemical bonds and molecules in the printed substrate (Gurses, Açıkyıldız, Güneş and Gürses, 2016).

Impact of Light on Colors

The part of a molecule responsible for its color is called a chromophore. The light that meets a painted surface can alter or break the chemical bonds of the pigment, causing colors to become bleached or changed in a process known as photodegradation. Materials that resist this effect are said to be light resistant (Evenson, 2003). Exposure to the portion of the electromagnetic spectrum that contains wavelengths of ultraviolet radiation accelerates the fading of the color. The photonic energy of ultraviolet radiation that is not absorbed by atmospheric ozone exceeds the dissociation energy of the carbon-carbon single bond, resulting in binding rupture and color discoloration. Inorganic colorants are considered more light-resistant than organic colorants.

During fading, pigment molecules undergo various chemical processes that cause discoloration. When an ultraviolet photon reacts with a molecule that acts as a pigment, the molecule goes from its fundamental state to an excited state. The excited molecule is highly reactive, unstable, and capable of destroying the pigments (Colombini, Andreotti, Bclasiaraldi, Degano, and Łucejko, 2007).

Five detailed classifications of the chemical reactions known to cause degradation in the color are presented by Peters and Freeman (1996). They are photolysis, photooxidation, photoreduction, photosensitization, and phototendering (Peters & Freeman, 1996).

Photolysis (photochemical decomposition) is a chemical reaction in which photons break down the compound. This decomposition occurs when a photon of sufficient energy finds a dye molecule bond with adequate dissociation energy. The reaction causes homolytic division in the chromophore system resulting in discoloration of the pigment.

Photooxidation (photochemical oxidation) is a reaction that happens when a pigment molecule is excited by a photon of sufficient energy and triggers an oxidation process. In the process, the colorant molecule’s chromophore system reacts with atmospheric oxygen to form a non-chromophore system, resulting in fading. Pigments containing a carbonyl group such as chromophores are particularly vulnerable to oxidation.

Photoreduction (photochemical reduction) is a reaction that happens when a pigment molecule with an unsaturated double bond or triple bond acts as a chromophore and experiences a reduction in the presence of hydrogen and photons of sufficient energy forming a saturated chromophore system. Saturation reduces the length of the chromophore system, resulting in the fading of the pigment.

Photosensitization (photochemical sensitization) is the exposure of stained cellulosic material, such as plant-based fibers, to sunlight, allowing pigments to remove hydrogen from cellulose, resulting in photoreduction on the cellulosic substrate. At the same time, the pigment will suffer oxidation in the presence of atmospheric oxygen, resulting in its photooxidation.

Phototendering (photochemical tender) is a reaction that happens when the substrate material supplies hydrogen to the pigment molecules due to the exposure to ultraviolet light, reducing the pigment molecule. As hydrogen is removed, the material undergoes oxidation.

In addition to light, other stimuli can influence color fade, including temperature, humidity, oxygen, rainfall, contaminants, and stress (Wypych, 2013). These stimuli influence color fade and product lifetime by causing chemical and physical reactions in the molecules. Commonly, colors fade with sufficient exposure to natural weathering; therefore, the extent to which this effect is tolerated can depend on the situation. For example, the expectations of the user and the lifetime of the product should be quantified to satisfy the expectations regarding durability and price (Wypych, 2013). Color and product lifetime prediction using weathering data interpretation is vital for researchers and manufacturers. Accelerated weathering conditions in a laboratory can quantify amounts of stimuli that affect product lifetime (Wypych, 2013).

Lightfastness Standards and Testing

Knowing where ultraviolet wavelengths are located in the spectrum is the first step in understanding how they affect the permanence of prints. They are in the range of 100 to 300 nanometers; thus, their wavelengths have a high frequency with higher energy. Red visible light has a longer wavelength and a lower frequency meaning that it is of a lower energy level when compared to UV light. Looking at the electromagnetic spectrum from right to left reveals that the wavelengths decrease, and the energy increases, as previously stated. The increase in energy has a consequent increase in radiation and an increase in the effect over matter (Rohrlich, 2020). In this case, the increase in energy causes fading of the color in the printed material. The resistance to this effect is called lightfastness which is most commonly tested in the laboratory using fade testing equipment designed to mimic the effects of natural light.

The process of testing the lightfastness degree was first used in the textile industry to test the resistance to fading in the presence of sunlight. With this process, the blue-wool scale was developed; this scale is made from a group of dyed wool strips. These strips are graded for their resistance to fading on a one-to-eight scale, one being very low fade and eight being very high fade. Each wool strip grade has been manufactured to fade at a specific predetermined rate. The test is performed by exposing the blue-wool strips alongside the print samples; both the strips and the samples have half of their areas covered to have a control side for each one. When the exposure is concluded, the samples are compared to a grayscale that indicates the level of fading, as stated previously, from one to eight (Zeller-Gmelin Corporation, 2017).

Exposure to Elements in Laboratory

In addition to the color characterization that represents a critical stage in the experiment, the effects of exposure to light on printed media were also central to the experiment.

Weathering chambers can simulate the natural conditions needed to complete many experiments, and they, therefore, help to test the ability of a material to withstand the effects of weather. The test chambers can measure variables such as humidity, ozone, light, and heat. The most common use of the weathering chambers is to test materials developed to endure external conditions.

Weathering chambers that use xenon arc lamps are considered the best way to simulate the full spectrum of sunlight, including ultraviolet, visible light, and infrared; the wavelengths present have a range from 295 nanometers to 800 nanometers. Since the weather chamber simulates sunlight, it needs to use filters to eliminate unwanted variables like radiation/heat, depending on the test parameters (Tobias & Everett, 2002a). In this case study, a xenon test chamber was used to set the appropriate spectral power distribution in specific conditions in order to quantify the lightfastness performance of the non-latex water-based inkjet inks and the water-based latex inkjet inks.

Image Stability

Printed images are often exposed to negative influences from external climate conditions. Several issues must be considered when testing for lightfastness: Light intensity, temperature, temperature sensitivity of materials, humidity, dark stability, linearity of degradation, reciprocity failure, and gas (ozone) fading. The existence of the different factors that have an additional effect on the ink stability makes any lightfastness test results variable. Therefore, if the parameters are not controlled or fully measured, exact predictions are not possible, but measurements in change can be achieved, taking into account that other possible factors are affecting the stability and lightfastness of the print (Tobias & Everett, 2002a).

Polymer Coatings for Lightfastness

The color fixing problem of inkjet printing is a primary concern for ink manufacturers. There are two kinds of inkjet inks on the market: dye-based ink and pigment-based ink. Most dye-based inkjet printing inks present poor waterfastness and poor lightfastness properties (Hoang & Kieu, 2017). Meanwhile, the use of pigments is faced with some difficulties in reconciling particle size and dispersion stability. Therefore, various attempts to develop colorants capable of improved lightfastness have been carried out. For example, there is a technique in which resins are added to the pigment ink. However, with this kind of ink, resin particles and pigments are separately dispersed so that the improvement in pigment dispersion stability is insufficient even when the viscosity of the ink is excessively increased. Therefore, in situations where the surface adsorbs the pigment, the use of a resin layer is proposed. The adsorption level can be controlled through the hydrophobic and hydrophilic moiety of the resin (Hoang & Kieu, 2017).

Previous research studies have examined the use of different polymers as additives in the ink formulation with respect to lightfastness. Resins and latex are two common additives in inkjet ink formulations. Epson uses resins because of their compatibility with the piezo-electric printheads, and latex is used by HP because of its compatibility with thermal printheads (Niemöller & Becker, 1999).

Chapter 3

Literature Review

Introduction

This chapter considers the literature relevant to the study of lightfastness. It presents background information, technical aspects, and previous studies that have evaluated the different variables tested in this study, lightfastness, and color, to help make clear how and why the research questions were formulated. This review provides a foundation to identify and formulate the parameters that have been set for the current study, such as substrate, type of ink, accelerated exposure, and measurement.

Lightfastness Tests on Conventional Printing Technologies

Lightfastness studies in the printing industry began with conventional printing technologies such as lithography. Lind, Stack, and Everett (2004) is an excellent example of a previous study of lightfastness on lithographic inks relevant today due to the process, measurements, and results. The purpose of the study was the quantification of the lightfastness of conventional lithographic inks exposed to extreme weather conditions while attempting to create a standard for testing lightfastness of inks and to develop a consistent methodology for subsequent research. This study presented various conclusions that met the expectations of the researcher in the present study. After the initial exposure of the specimens in an accelerated aging chamber commonly referred as lightfastness chamber, the inks were discriminated between good performing inks and bad performing inks. In the eight colors chosen for this study, three were different types of yellow, which were also discriminated by their performance even though their initial appearance was similar. This one detail shows how much the formulation of the ink can influence its properties and performance. The examination of previous studies is challenging since the different types of inks, and their properties behave differently from newly developed high-performance inks.

When looking for relevant studies that tested the lightfastness of inks and used a similar process as the ones mentioned previously, the researcher found Narakornpijit's (2018) study that tested lightfastness on high-chroma water-based flexographic printing inks. The application of this experiment is different from the current study because it examined the lightfastness characteristics of high-chroma water-based flexographic printing ink sets within the context of package printing applicability. In addition, this study also examined whether high-chroma inks presented different lightfastness characteristics when compared to conventional water-based flexographic inks. Narakornpijit's study presents how high-chroma inks are more lightfast than water-based flexographic inks and how even though its lightfastness degree is higher, the ink formulation can present limitations on its applications (Narakornpijit, 2018).

Lightfastness Tests on Inkjet

The development of high-performance inkjet printers and inks has advanced rapidly. Manufacturers have continually been creating and introducing new inks and technologies for inkjet printing. However, chemists are still challenged by how difficult it is to combine the wide gamut present on dye-based inks and the light and weather fastness characteristics that the pigment-based inks possess into the new ink formulations. In a 2005 study by Chovancova and associates (2005), three sets of different inkjet printers, inkjets inks, and experimental substrates were subjected to printability tests to evaluate the interactions between ink, printer, and substrate. Color gamut and color accuracy were compared between the ink/printer/substrate sets, and the results were expressed in terms of gamut volume and CIE L*a*b* coordinates. Furthermore, lightfastness tests were performed, and the results were expressed in terms of change in gamut and color profile. The outcome of the experiment exposed how the ΔE values for most of the sets were generally under two, and when compared, the measured samples were close to the values from the original reference sample. Therefore, the researchers concluded that most of the color shift happened during the earlier time period of exposure during the accelerated fade test (Chovancova et al., 2005).

In a similar study on lightfastness properties, Rice & Fleming (2007) emulated many of Chovancova and associates (2005) methods. The focus of the study was not ink sets but different printers and substrates. The experimental procedure was also refined in order to shape the study for thermo-sensitive ink sets and the use of different test targets. RGB test targets were chosen specifically because the driver of one of the printers used in the study recognized the printer as an RGB device, and the use of different targets would not provide an accurate outcome. After the proposed method was performed on all printers and substrates, the researchers were able to identify the shift in color gamut for each and point at the reasons why the shifts were happening as the final outcome (Rice & Fleming, 2007).

Although the researchers utilized the same test structure, some factors obligated the researchers to make requisite changes. The outcomes cannot be portrayed as similar or different since the variables were not equal. Each study presented different outcomes for their unique variables, and each were successful in addressing their respective research questions.

Latex Inks

Ink developers have been exploring ways to disperse the light particles away from the ink particles in a way that the reaction will be smaller, and the degradation will take longer. Using additives in the ink formulations is a way of increasing the activation energy barrier (Lovell, 2006).

Until 2008, the top three digital printing technologies used were aqueous, commonly known as water-based inks, solvent-based inks, and UV-cured inks. water-based inks were primarily intended for indoor use. They performed well in terms of image quality and color gamut size; durability and the need for waterproofing meant the inks were not suitable for outdoor applications.

Solvent-based inks are primarily intended to be used for outdoor signage. They are water-resistant, and their UV stability makes them a preferred option for wide-format and outdoor applications. The cost of production of solvent-based inks became a limitation and drove the industry to create eco-solvent inks. These inks were developed as an economical alternative to traditional solvent inks by removing some of the most expensive chemicals in their formulation (Van Greunen, 2021).

Eight years after patenting the first claims of latex as an additive that would improve the stability of the image on printed media for inkjet inks, latex inkjet ink technology was introduced by Hewlett-Packard (HP) in 2008 for wide-format graphics printing applications. After an extended period of beta-testing and an economic recession, latex inkjet ink went mainstream in 2010 (Boer, 2012).

The patent for the invention of latex polymer blends claims that their use as an additive renders inkjet inks water-dispersive and light-dispersive. This would enable the formation of durable ink films on inkjet printed media. The description of the patent indicates how inkjet inks include a vehicle and a colorant. The colorant is associated with a primer core/shell polymer to form a primer/colorant combination. This combination results in the polymer encapsulating the colorant, forming what is known as a durable core/shell polymer. The primer core/shell polymer promotes the adhesion of the durable core/shell polymer to the colorant and disperses the colorant in the ink. The durable core/shell polymer provides a smear-fast film upon drying of the ink on a print medium (Nguyen & Ganapathiappan, 2000).

Studies Focused on Image Stability

When image stability is studied under the exposure of light only, lightfastness is often the term referred to. However, lightfastness can be further sub-divided to address specific chemical reactions to exposure. In the study “Stability Issues and Test Methods for Inkjet Materials.” Vogt (2001) divided lightfastness into photooxidation, photo-reduction, and photocatalysis (Vogt, 2001).

The most relevant findings of Vogt’s study in image stability that relate to the present research were the test conditions and the target specifications needed to produce reliable data for a comparison study. Vogt developed a target created specifically for her study. One part of the target contained 100 percent density patches for each CMYK. RGB colors were reproduced in a 10 step (10 to 100) scale of both densities and dot percentages. Concerning the room test conditions, temperature and humidity control levels were monitored and documented for consistency. In addition, a constant humidity level between 50% and 63% was essential for the stability of the substrate as a carrier. Regarding the handling of the samples, Vogt’s study (2001) suggested that the targets be kept in the dark under the same ambient conditions before, during, and after the test period and be monitored during the test period.

The scope of a study determines the appropriate measurement test periods that can address the proposed research questions. In the case of the study presented by Tobias and Everett (2002), instrumental colorimetric and densitometric readings on four sample areas were taken every 10 hours. This procedure provided the means to observe changes and calculate the final time interval of exposure needed for the desired effect on ink stability. Consequently, the rest of the sample could be exposed to a set time that would be continuous and repeatable for all different iterations. The most important finding in this study is the indication that black inkjet inks are less affected by natural and accelerated lightfastness tests; because of this, the researchers propose that black inks should provide excellent stability on coated and uncoated substrates (Tobias & Everett, 2002).

Comparisons made between correctly handled samples result in readings that can be trusted when using high-end measuring devices such as spectrophotometers. Problems with colorimetry and densitometry can arise during the test portion of the study, as stated by McCormick-Goodhart and Wilhelm (2003). Densitometric readings on neutral gray patches can produce inconsistent visual predictions across different substrates and inks. Therefore, the colorimetric approach was taken in the present study to avoid any inconsistent visual predictions or readings.

Studies on Light Sources

In lightfastness testing, standards are of most importance to have a continuous method and reliable data for comparison purposes. To reach this, Pugh and Guthrie (2001) explained two items in their study, the development of lightfastness testing and lightfastness standards. Theories of light-induced fading and degradation, the concept of standards and standardization, and instrumental lightfastness and weather fastness testing were the items that the researchers introduced. These theories on light-induced fading and degradation were developed to clarify how the ink particles and the ink formulation behave when exposed to light, how standards are created and managed by the international organization for standardization (ISO), and why instrumental lightfastness testing is preferred overexposing the samples to natural light (Pugh & Guthrie, 2001).

It is generally accepted that the effect of light on the samples presented by Pugh and Guthrie (2001), using an accelerated method, is difficult to standardize because of the anomalies which can be present. However, it is even more complicated to standardize the exposure to natural light since it depends on additional variables that cannot be controlled, such as location, weather, and seasonal changes.

Lucas (2001) presented several testing options, where the approach changes depending on what needs to be accomplished. In this case, the focus was on accelerated testing since natural exposure to light is time-consuming. In addition, natural exposure to light presents variables that cannot be controlled, thus affecting the final results. In accelerated testing, carbon arc and xenon arc lamps have been used, but according to Lucas, the use of carbon arc lamps can yield valuable data; however, xenon arc lamps are more accurate and better for correlating to the solar spectrum. Therefore, using xenon arc lamps during the accelerated exposure testing is the preferred method to test for fading and image stability.

Effects of Substrates on Image Stability

According to Chovancova (2005), in several of their studies on lightfastness, the effect of the substrate on the lightfastness of a printed image is high enough that it is critical to the study to know its characteristics. For example, Lovell (2006) explained in “Inkjet Inks and Substrates - Novel Approaches for Their Physical and Optical Properties Characterization” that a substrate characteristic, such as the use of optical brightening agents (OBAs),[2] can also have an adverse effect on the lightfastness degree since it can accelerate metamerism and cause color shifts and yellowing over time. The decomposition of the OBAs can also cause yellow stains on the print. Agreeing with this is the study presented by Tobias and Everett (2002). It is concluded that after studying different types of substrates under accelerated lightfastness testing, inkjet inks printed on coated substrates are more susceptible to UV degradation than those printed on a bond or uncoated substrate.

Internal and surface sizing are two other characteristics that are important to consider. According to a study by Pap, Agate, and Fleming (2007), the tendency of surface sizing is to reduce the absorbency of the substrate due to a reduction in porosity, and internal sizing has the opposite effect. This can affect the gamut size of the sample because less absorbency results in a larger gamut, and the more absorbency, the smaller the gamut size. An understanding was gained that the effect of the substrate on the experiment itself is important to discriminate if a change is relevant and caused by the degradation of the ink, the degradation of the coating, or both.

Interaction of the ink with Coated Media

The increased demands on photorealistic and large format printing have brought a focus on the development of coated media for inkjet printing. In addition to OBAs, coating formulations can be comprised of fixing agents, polymers, and many

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[2] Optical brighteners are widely used to hide the yellowish tint of paper substrates by giving them a bluish tint and to increase superficial whiteness of the product in order to enhance color gamut and color density (Rasmusson et al., 2005).

other components. The image quality, fastness properties, and the rate of absorption are at stake when choosing the components that will make part of the substrate coating (Lavery & Provost, 1999).

Inkjet inks and the surface of an uncoated paper are both anionic, and therefore there is no attraction between them. The lack of attraction between the inks and substrate can lead to problems in the printing process, such as curl and slow drying. When the ink colorant is printed on the substrate, it needs to be immobilized immediately on the surface of the substrate and separated from the carrier. The problem lies in the time it takes the substrate to absorb the ink. If it is absorbed too fast, optical density will be decreased. If it is not absorbed fast enough, it can cause a lateral spread that will result in color-to-color bleeds. A viable balance between the two effects can be achieved by manipulating the porosity and absorbency of the substrate by the use of a sizing coating on the substrate (Svanholm, 2007).

Chapter 4

Research Objectives

This thesis experiment explored the difference in lightfastness between two types of inkjet inks. With the use of an accelerated weathering chamber and measuring tools, the study examined whether the latex as an additive on the ink formulation resulted in a difference in the lightfastness of the sampled inks. It was the objective of this study to improve the understanding of a key performance aspect of commercially available latex inkjet inks.

Research Questions and Hypotheses

This study sought to answer the following questions for each phase of the experiment using non-latex water-based inkjet inks and latex inkjet inks:

1. Is there a difference between the exposed and un-exposed printed samples?
    - 1.1 After exposure to accelerated weathering conditions, is there a difference in the colorimetric values between the samples?
    - 1.2 After exposure to accelerated weathering conditions, is there a difference between ΔE_{00} cyan on water-based and ΔE_{00} cyan on latex?
    - 1.3 After exposure to accelerated weathering conditions, is there a difference between ΔE_{00} magenta on water-based and ΔE_{00} magenta on latex?
    - 1.4 After exposure to accelerated weathering conditions, is there a difference between ΔE_{00} yellow on water-based and ΔE_{00} yellow on latex?

1.5 After exposure to accelerated weathering conditions, is there a difference between ΔE_{00} black on water-based and ΔE_{00} black on latex?

2. After exposure to accelerated weathering conditions, are there color sections critically affected by the exposure?

Hypotheses

The above research questions lead to the following hypotheses:

1. $H_0: \Delta E_{00_{water-based\ ink}} = \Delta E_{00_{latex\ ink}}$

   $H_1: \Delta E_{00_{water-based\ ink}} \neq \Delta E_{00_{latex\ ink}}$

2. $H_0: \Delta E_{00} cyan_{water-based\ ink} = \Delta E_{00} cyan_{latex\ ink}$

   $H_1: \Delta E_{00}\ cyan_{water-based} \neq \Delta E_{00}\ cyan_{latex\ ink}$

3. $H_0: \Delta E_{00}\ magenta_{water-based\ ink} = \Delta E_{00}\ magenta_{latex\ ink}$

   $H_1: \Delta E_{00}\ magenta_{water-based} \neq \Delta E_{00}\ magenta_{latex\ ink}$

4. $H_0: \Delta E_{00}\ yellow_{water-based\ ink} = \Delta E_{00}\ yellow_{latex\ ink}$

   $H_1: \Delta E_{00}\ yellow_{water-based} \neq \Delta E_{00}\ yellow_{latex\ ink}$

5. $H_0: \Delta E_{00}\ black_{water-based\ ink} = \Delta E_{00}\ black_{latex\ ink}$

   $H_1: \Delta E_{00}\ black_{water-based} \neq \Delta E_{00}\ black_{latex\ ink}$

Chapter 5

Methodology

From a postpositivist worldview, the appropriate research design for this study followed an experimental quantitative research design. As stated by Creswell (2013), a postpositivist worldview holds a deterministic philosophy in which causes determine effects or outcomes. A postpositivist worldview works well with an experimental design because it looks to support or not support previously stated claims based on past studies that tested similar variables and samples.

Sample Development

For this study, printed samples were used to determine the difference between the effect of accelerated light exposure on water-based inkjet ink and water-based inkjet ink with latex as an additive. During the experimentation phase, samples consisting of four spot color patches that contain cyan, magenta, yellow and black were used.

The color patches were printed using an available synthetic satin velvet blockout film substrate that works with both printing inks. Since the same substrate was used for both inks, measurements taken on the non-image area allowed the interpretation and consistency of the other measurements (Pap et al., 2007). In addition, the satin velvet blockout film substrate was chosen for its capability with both water-based and latex inkjet inks.

The researcher used three sets of prints for each type of ink. Each sample was measured before entering the weathering chamber and was exposed at the same time to reduce any variability due to aging on the light emitted by the xenon lightbulbs. Measurements were divided into zero hours, 48 hours, and 96 hours of exposure.

The sets used were formed by four patch count test strips that were used to test the variables. The patches used were the solid cyan, magenta, yellow, black, and non-image area. The independent variable for this experiment was the time under light exposure inside the chamber, and the dependent variable was the change in color as expressed as ΔE_{00}. This was, as stated by Creswell (2013), an approach for testing objective theories by examining the relationship among variables.

Testing Devices

The device used to perform the accelerated fade testing of the samples was the Q-SUN Xe-1 Xenon test chamber. This chamber can accelerate the damage caused by UV light exposure and provides the researcher with a controlled testing environment that allows the repeatability of the test. The settings used for this specific test were: window glass filter, irradiance level at 1.10 W/m2, relative humidity at 50%, and test intervals of 48 hours and 96 hours. The Q-SUN Xe-1 tester’s slide-out specimen tray is 251×457 mm (9.88×18 inches). This limited the sample size but allowed a dedicated and controlled environment where the size of the sample and the physical distribution of the light inside the chamber did not vary. Consistent with previous studies (e.g., Wilhelm et al. 2020), a 1.10 W/m2 irradiance was used, and samples were measured at 48 hours as suggested by the findings in previous studies. In this specific case, the samples were measured using a spectrophotometer before fading simulations. Then, they were submitted to 129,600 kJ/m^2 of energy over 48 hours and measured again. This represented about 4.5 months of daylight exposure in Florida (Rasmusson et al., 2005). The samples before and after measurements were compared using the X-Rite eXact to display changes in terms of specific L*a*b* color values. The color variations were then compared between the various inks and substrates, and results were documented.

Measurements

Measurements were taken on all samples before and after exposure. The measurements were taken three times per patch per sample to provide higher accuracy. Acquiring the L*a*b* values from the measurements performed on four specific patches representing CMYK solid colors and non-image area allowed the researcher to calculate the ΔE_{00}, interpret how the different inks behaved under the accelerated light exposure, and determine if the difference was significant and noticeable to ascertain if there is any difference.

Previous Evidence

There is evidence that in the four-color printing process, which uses cyan, magenta, yellow and black ink, the fading problems are more common in the magenta and the yellow. Yellow pigments absorb primarily blue light, which is at the high-energy end of the visible spectrum. Without any protection, yellow is expected to show a more significant loss in color shift than any other color. Magenta has a different problem. It absorbs green light, and the intensity of visible sunlight peaks in the green. UV absorbers have little effect on magenta fading because they do not absorb green light. Magenta fading is thus expected to be due mainly to the absorption of green light. Small changes in magenta density are more visible to the human eye than similar changes in yellow density (Lucas, 2001).

Process

The following steps were taken for both non-latex water-based inkjet inks and latex inkjet inks to resolve the research questions stated previously.

1. Was there a difference between the exposed and un-exposed printed samples?
    1.1 After exposure to accelerated weathering conditions, was there a change in the colorimetric values between the samples?

    Keeping the un-exposed printed sample in a dark environment ensured that the measurement was not contaminated by light. Additionally, the measurements on both samples were taken one right after the other, thus eliminating any changes due to the original composition of the ink and its reaction with the substrate or other variables in the environment.

    The measurements were performed using an X-Rite eXact. The researcher followed the procedures as recommended by the manufacturer. (X-Rite, n.d.)

    Performing the same steps to measure the exposed samples displayed the L*a*b* values for the exposed samples. Having the two sets of measurements, the researcher proceeded to calculate the ΔE_{00} and find if there were any colorimetric differences.

2. After exposure of the samples to accelerated weathering conditions, were there critical color sections with visible physical degradation as an effect of light exposure?

This section of the experimental phase was only considered if the researcher perceived a noticeable visible physical degradation on any of the samples or if there were any outliers in the results to the first question that were not what previous studies indicated as expected behavior.

Calculations

The resulting calculations and subsequent differences were compared between the two types of ink for each category as follows:

$$\Delta L^{*}a^{*}b^{*}\ Inkjet\ ink\ vs\ \Delta L^{*}a^{*}b^{*}\ Latex\ inkjet\ ink \tag{1}$$

Comparing the behavior of the inks, the researcher interpreted the information and determined which ink and color were less affected by the exposure to light in the weathering chamber.

Chapter 6

Results

This chapter presents the measurement results for ΔL*, Δa*, Δb*, and ΔE_{00} values for each ink in the study. The data sets were compared between water-based inkjet inks and latex inkjet inks following the research questions using descriptive analysis of the metrics. The graphs represent correlations of ΔE_{00} through timed exposure periods of 48 and 96 hours.

Water-Based vs. Latex

According to previous studies in the four-color printing process, which uses cyan, magenta, yellow and black ink, the fading problems come primarily from the magenta and the yellow. Yellow pigments absorb primarily blue light, and magenta aborb green light. Blue and green light are present in the area of the visible spectrum were the sunlight peaks. Thus, a fade in magenta and yellow is expected.

When the results gathered through three measurements for each color in three separate samples for each type of ink were analyzed, the unexpected results did not agree with what the researcher expected based on the study performed by Lucas in 2001.

After 48 hours of exposure, the measurements presented a greater change in the cyan and magenta ink and the lowest in the yellow ink. Evidence of studies performed with other technologies and inks led to the expectation that the fading of yellow and the magenta would be higher than the other inks after an accelerated exposure.

Measurements showed that for the 48-hour exposure, magenta and cyan had a larger difference between the unexposed and exposed measurements. With this measurement, the proposed and expected results for the 96-hour exposure would be a linear increase in the ΔE_{00} for magenta and cyan, Figure 1 shows that cyan had the largest ΔE_{00}.

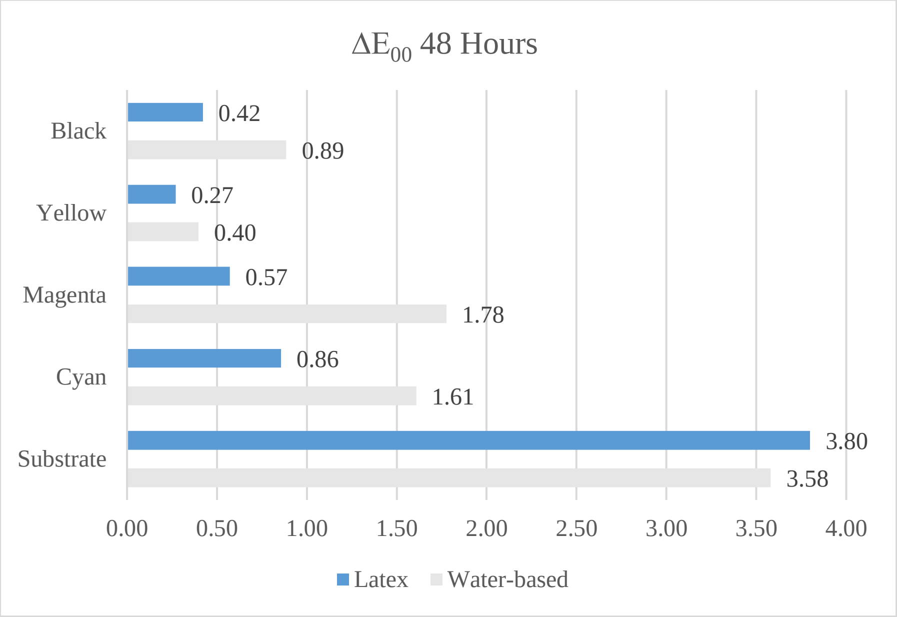

Figure 1. Averages of ΔE_{00} for each color and non-image area over a 48-hour exposure on water-based inkjet and latex inks.

Figure 2 shows the results of calculations for ΔE_{00} after 96 hours of exposure, and a behavior change can be observed. After 96 hours, the ΔE_{00} for cyan was greater than the ΔE_{00} for the magenta, compared to the measurements taken at 48 hours where the ΔE_{00} for the magenta was greater than the ΔE_{00} for the cyan, this being true only for the water-based inkjet inks. In the case of latex inks, one can see a linear change occurred among measurements across all colors.

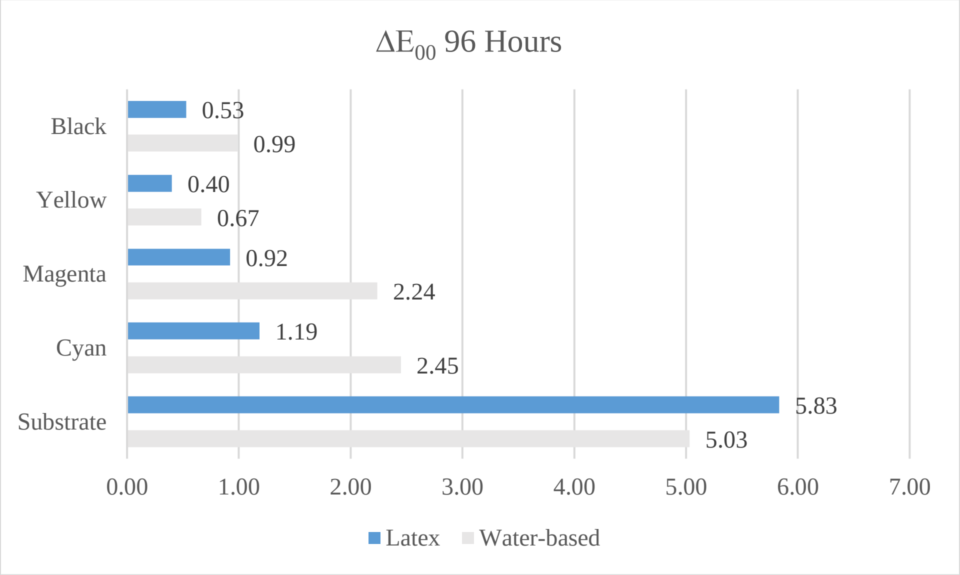

Figure 2. Averages of ΔE_{00} for each color and non-image area over a 96-hour exposure on water-based inkjet and latex inks.

In examining the colorimetric differences, it is curious that the substrates differed. There is no identifiable reason why the substrate adjacent to the standard water-based inks would exhibit different lightfastness characteristics when compared to the latex water-based inks. Therefore, the variation noted can be useful as a reference to describe the uncontrolled variation in the present study. As illustrated in Figure 2, after 96 hours the differences in the substrates were recorded at 5.83 ΔE_{00} and 5.03 ΔE_{00}; a difference of 0.8 ΔE_{00}. When examining the colorimetric values of the inks, only the magenta and cyan exceed this difference, at 1.32 and 1.26 ΔE_{00}, respectively.

According to the data collected, the color that had the greatest difference between the unexposed and the exposed samples after 96 hours was cyan. A more detailed analysis therefore ensues. Figure 3 shows that the color cyan had a greater variation in the b* axis, representing the yellowness to blueness. It means that inks shifted in color and became less blue and consequently more yellow.

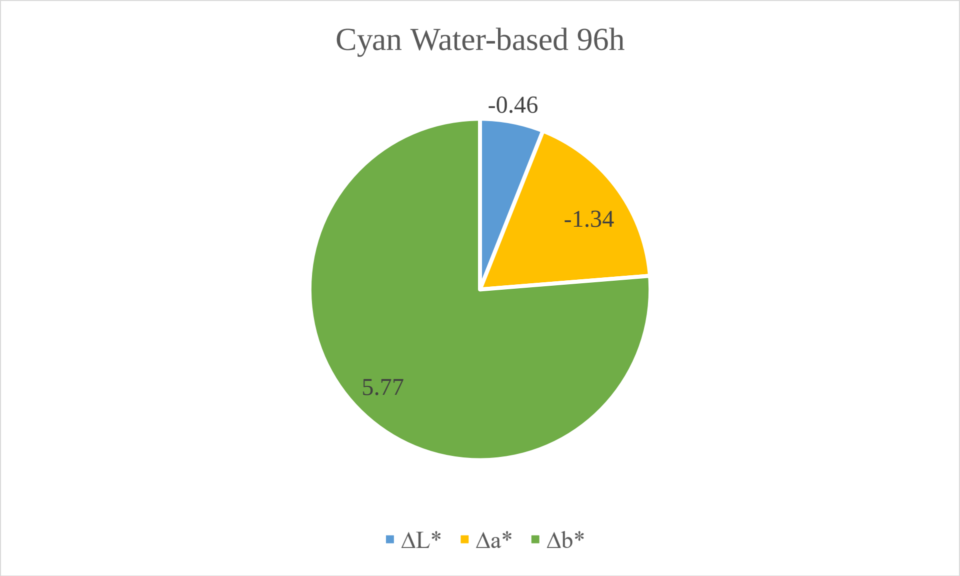

Figure 3. ΔL* Δa* Δb* of the cyan water-based ink over 96 hours.

On the other hand, Figure 4 demonstrates that the cyan latex ink had a greater variation on the a* axis, which represents redness to greenness. The cyan ink shifted in color and became less red and, consequently, more green. The slight change on the b* axis represents higher stability on that specific color making it more lightfast than the water-based ink.

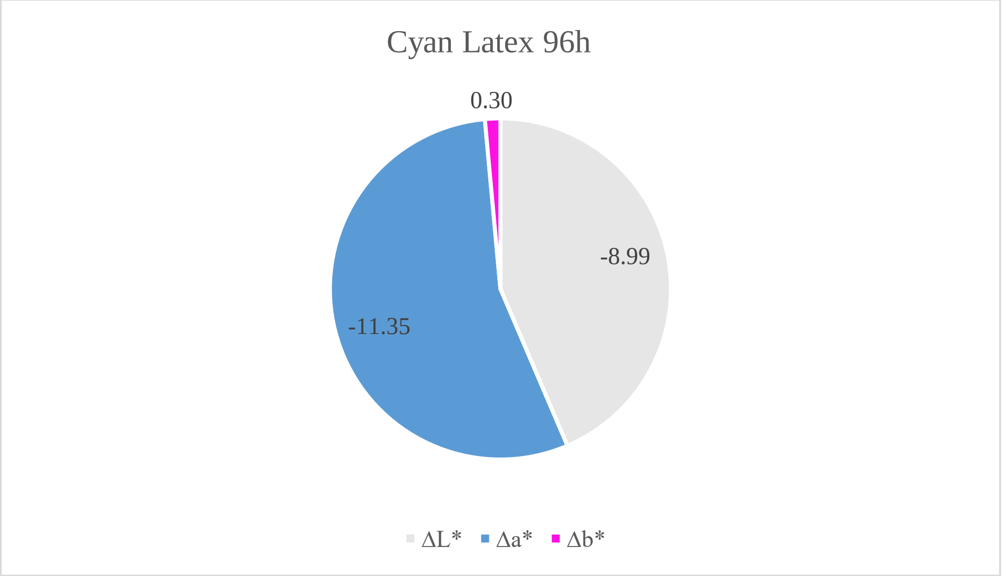

Figure 4. ΔL* Δa* Δb* of the cyan latex ink over 96 hours.

Color Shift

Figure 5 represents the color shift on the L*, a*, and b* axes of each color measured on the water-based inks after 96 hours of accelerated exposure to light. The color shift on water-based ink is more prominent towards the Δb* axis, meaning that most of the colors are shifting on the yellow to blue axis. The only outlier is the color yellow, where the shift is stronger on the Δa* axis. This is similar to what occurs in the latex ink, where all colors have a stronger shift on the Δb* axis.

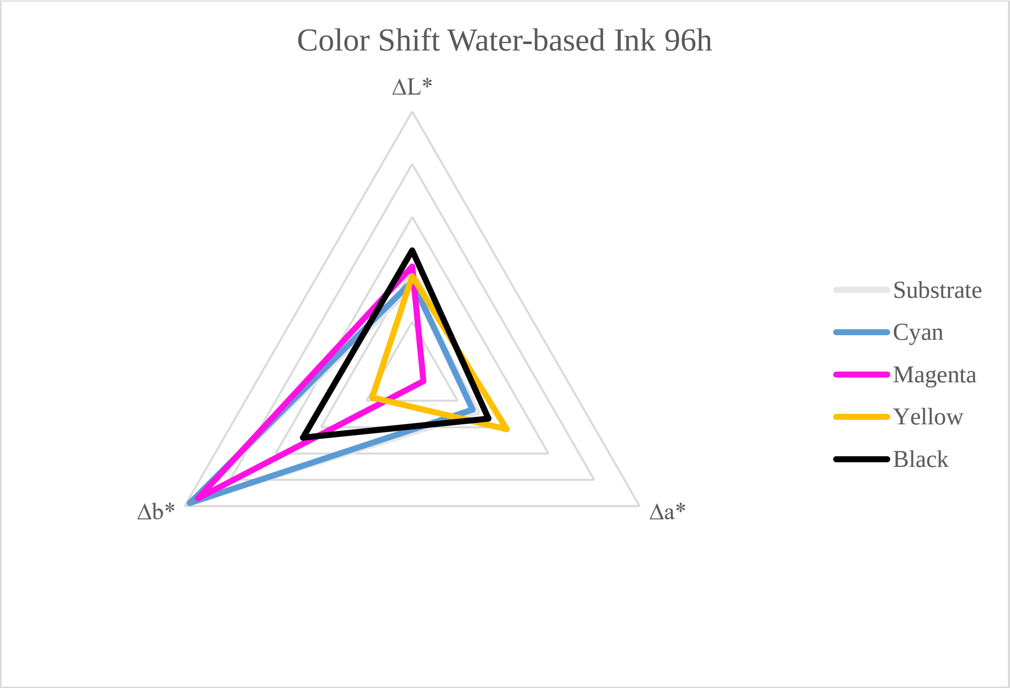

Figure 5. Color shift of the CMYK water-based inks over the L*a*b* axis.

In Figure 6, the individual values for Δb* in both inks, water-based and latex, show that the shift in the Δb* moves towards the yellow color. This behavior has been seen in other technologies where the color shift in the cyan color is so strong that it can degrade to a point where it fades.

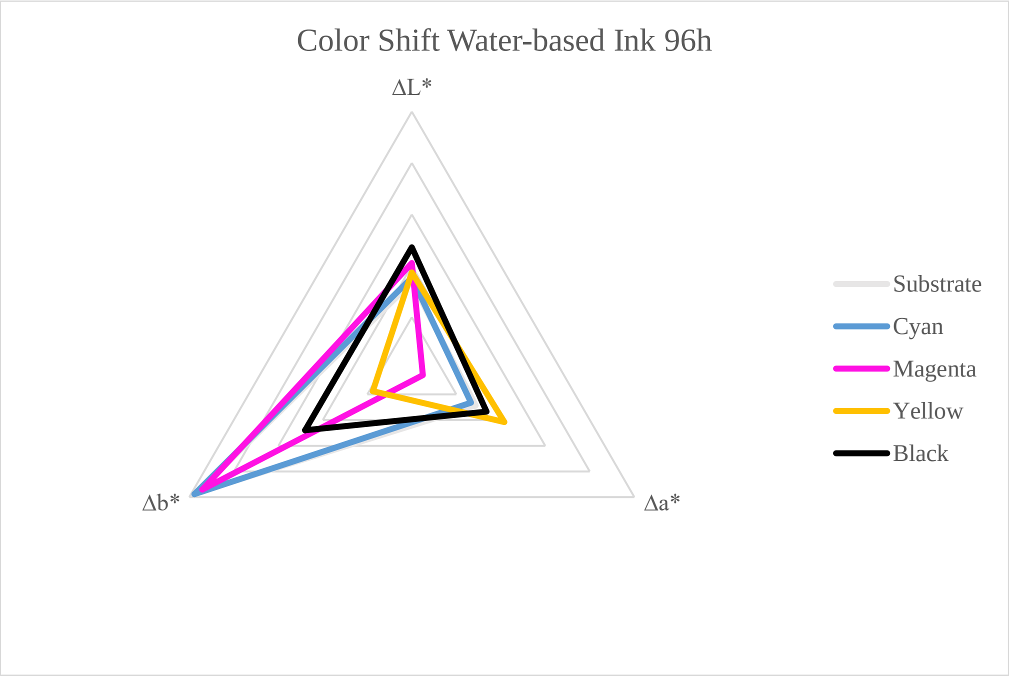

Figure 6. Color shift of the CMYK latex inks over the L*a*b* axis.

Chapter 7

Summary and Conclusions

The following research questions were answered by analyzing the data gathered in the experiment. Conclusions and suggestions for further research follow.

Research Question 1: Is there a difference between the exposed and unexposed printed samples?

The results of the experiment can be answered by looking at the ΔE_{00} for each color on both technologies shown in Table 1.

Averages ΔE_{00} 96 Hours					
	Substrate	Cyan	Magenta	Yellow	Black
Water-based	5.03	2.45	2.24	0.67	0.99
Latex	5.83	1.19	0.92	0.40	0.53

Table 1. ΔE_{00} for each color measured on water-based and latex samples.

RQ.1.1. As expected, there were changes in the colorimetric values between the unexposed and exposed samples. Looking at Table 1, one can see that none of the values are zero, which means that there was change in the areas measured. Even though none of the values are zero, the change in yellow and black is less than one. Because of this, the change in yellow and black inks can be considered negligible. Table 1 presents a clear view of how the water-based inkjet ink is less stable than the latex inkjet ink on all measured colors.

RQ.1.2. The colorimetric difference, ΔE_{00}, on the water-based and latex ink for the cyan color was over one, commonly recognized as a noticeable difference. The value for the water-based ink was higher than the value for the latex ink, indicating that the cyan ink on the water-based inkjet ink was more prone to fade. Nevertheless, in Table 2 the difference between the two measurements, before and after 96 hours of accelerated exposure to light are presented and represent the direction of the shift in the CIELAB color space. In this case cyan had a negative shift on the L* axis meaning that it lost brightness, a negative shift on a* meaning it is shifting towards the green, and a larger positive change on the b* which means that the cyan ink is shifting towards the yellow. A possible interpretation of this data could mean that the cyan is being affected the most on the b* axis which means that is losing its blue and gaining yellow components.

Original vs 96h Exposure Shift			
	ΔL*	Δa*	Δb*
Substrate	-0.64	-1.13	5.66
Cyan	-0.46	-1.34	5.77
Magenta	0.11	60.85	5.41
Yellow	-0.26	0.16	-2.25
Black	0.72	-0.64	0.80

Table 2. Difference in color shift for water-based inkjet inks after 96 hours of accelerated exposure.

In the case of the latex inks the behavior is completely different. Table 3 shows the strongest shift in the cyan ink is happening along the a* axis which means it is shifting towards the green even though the ink stays stable on the b* axis.

Original vs. 96h Exposure Shift			
	ΔL*	Δa*	Δb*
paper	-0.88	-1.26	6.24
cyan	-8.99	-11.35	0.30
magenta	-7.27	3.78	10.59
yellow	-1.37	0.38	14.61
black	0.72	-7.02	6.51

Table 3. Difference in color shift for latex inkjet inks after 96 hours of accelerated exposure.

RQ.1.3. The colorimetric difference, ΔE_{00}, of the water-based and latex ink for the magenta color had a relatively greater difference when compared to the other inks. This suggests that one should consider the less permanent behavior of magenta when choosing between types of inkjet inks. The behavior of this ink is congruent with previous studies on other printing technologies where it is stated that the magenta ink will present a greater reaction to light exposure when compared to other inks.

RQ.1.4. The results for the ΔE_{00} calculations for the yellow ink on both Water-based and latex inkjet inks are similar and could be considered a very stable color since the ΔE_{00} is not greater than one. Even though this can be said by looking at the measurements taken on the yellow samples alone, making a visual and instrumental inspection of the substrate, one can see that the substrate presented yellowing, and this could possibly affect the measurement on the yellow sample. It can be speculated that the yellowing of the substrate is adding yellow components to the yellow sample thus making the yellow sample more yellow and, in this case, countering the fade of the yellow ink.

RQ.1.5. Similar to the yellow color, the black ink did not have a ΔE_{00} larger than one. The results show that the color shift between the two technologies was less than that of cyan and magenta. Black has been known to be a more stable color in various printing technologies, and this outcome was expected.

Research Question 2: After exposure to accelerated weathering conditions, are there color sections critically affected by the exposure?

No sections were critically affected by the exposure. All color patches presented enough ink material to be measured.

Conclusions

There were differences in lightfastness characteristics regarding colorimetric attributes between water-based and latex inkjet inks. The latex inks demonstrated higher lightfastness than the water-based inkjet inks. This result was apparent from the measured samples and calculated colorimetric difference between exposed and unexposed samples. Some of the color shifts occurred as expected based on the results of previous studies that were performed with inks used in other printing technologies, such as the study presented by Lucas (2001), where evidence showed that magenta and yellow inks are more susceptible to fading when exposed to sunlight.

When looking at the substrate, yellowing was observed, and there was a cyan color shift from the blue side to the yellow side of the b* axis. There were no noticeable differences between exposed and unexposed samples upon initial visual inspection. However, there were measurable differences when colorimetric tests were performed using an X-Rite eXact spectrodensitometer. Based on these results, the latex inkjet inks presented more fade resistance than the water-based inkjet inks under the conditions used for this study.

The collected data presented several variations that were unexpected and surprising. The inks within each category (water-based/latex) would commonly have a similar overall behavior in terms of colorimetric shift when measured after the exposure in the weathering chamber. However, the yellow water-based ink had a color shift that was noticeably different from the color shifts of the other inks present in the water-based. While the cyan, magenta, and black inks had their strongest shift on the b* axis, the yellow ink had its strongest shift on the a* axis.

Previous studies also presented evidence that the inks with a stronger change would have been the magenta and yellow inks. However, in this study, the magenta and cyan ink were less lightfast than the yellow ink. According to the data gathered, the yellow ink did not have a significant change when compared to the data of cyan and magenta.

Attempting to discover all of the causes for this change would require a complete study on the specific chemical formulation of the yellow water-based ink and how each of its components is affected by light separately. However, without conducting a complete study on the ink formulation, we can still focus on one factor, namely, the behavior of the substrate. The degradation of the substrate could be contributing to the behavior of the yellow ink. As one can notice in Figure 6, the shift in the non-image area of the substrate is happening on the b* axis, where the average b* before the test was -7.9 and the average b* at 96 hours of exposure was -1.53. The direction of the shift is positive, which means that the substrate is yellowing. The effect of yellowing on the substrate might be due to the curing process in both printers used, with a temperature that reaches over 100 degrees Celsius. This can start the degradation process of the substrate, not only because of the exposure to light but also the exposure to heat. In the case of this specific substrate, the effect of the heat can be important since it is synthetic, and heat can affect some of its characteristics.

With the data gathered from the measurements on the non-image area of the substrate, one can speculate that the yellowing on the substrate is affecting the measurements on the printed area. The yellow ink should have faded, but because the substrate is yellowing during the test, that shift is helping the yellow to appear as if it didn’t change.

The focus on the behavior of the substrate provides the opportunity for a number of new possible studies that could solve many of the unknowns.

Implications

Water-based inkjet printing, since its creation, had been largely limited to indoor applications. The introduction of latex inkjet inks will allow the constituents to move toward wide format outdoor signage applications as a result of the improved lightfastness and waterfastness.

Additionally, as the printing industry is shifting towards multi-product, high-mix, low-volume, and digital on-demand production, inkjet, with the introduction of latex inks, becomes a more versatile technology that can fulfill these requirements without an increase in production costs or an increase in production time.

In addition, the search for more environmentally friendly products and manufacturing processes is currently a primary focus in industry and society. Latex inkjet inks contribute to this goal while maintaining the advantages of inkjet technology. Latex inks do not emit any hazardous vapors since the ink itself is comprised mostly of water and does not contain volatile organic compounds found in solvent-based inks. In addition, Inkjet technology offers decreased spoilage as a result of a lower consumption of ink. This allows latex inks to align with the goals of minimizing the environmental impact of the industry.

Limitations and Future Research

The present study presents potential limitations. For example, the chosen size of the sample due to the size of the testing equipment limited the number of samples and subsequent data points, together with the unexpected behavior of the substrate. These limitations are important for new and future research and can be a starting point to focus on when replicating or adapting the proposed methodology to new technologies being studied.

One limitation for the present study resulted from the relatively small size of the Q-sun chamber, which restricted the size and quantity of the samples that could be introduced. A larger chamber would have permitted the use of more samples leading to the study of different variables in the color spectrum. This would have provided an opportunity to investigate the behavior of density and gamut volume for each type of ink, using tints, solids, and process colors. The researcher suggests that this represents a potential direction for further research.

The idea that accelerated testing for digital media is accurate presents a new limitation since the concept of reciprocity failure was linked to unexpected behavior of printed samples under real life conditions. The concept of reciprocity failure in this case describes the idea that inks fade faster when exposed to lower light intensity for longer periods of time than what would be predicted when exposing them to high light intensity for a shorter period of time in an accelerated test chamber (Guo, Shilin; Miller, 2001).

To explain this, one cannot assume that the result of exposing the sample to double the amount of light in half of the time would be the same as the cumulative exposure to natural light. However, accelerated lightfastness testing has never presented exact results, it is only a way to give an approximate lightfastness degree of the setup consisting of inks and substrate.

When interpreting the lightfastness degree, the yellowing of the substrate has to be considered; for example, a substrate that presents yellowing will affect the ink that overprints it. A possible solution to this would be having an ink film with a higher thickness that will result in a more lightfast print since there will be more pigment particles in a given area and will withstand a more prolonged exposure to light, but a thinner ink film will be less lightfast and will be affected by any change that is presented on the substrate itself. One example of this is the halftone screened areas of the print where lightfastness will be generally lower than in the solids. This presents a possibility for a future study since the behavior is different between halftones and solids, and the behavior of the substrate will add to this change in behavior. Both areas represent important sections on the print production industry as the development of inks and printers that can use almost any type of substrate is growing. The current study shows that the ΔE_{00} measurements of the non-image part of the substrate after accelerated exposure were higher than the ΔE_{00} for cyan, magenta, yellow and black. Studying how specific inks exposed to light behave on different substrates and how the substrate characteristics affect the lightfastness of the inks would also be useful.

In addition, weathering chambers can simulate the natural conditions aside of light needed to complete some experiments. Therefore, they can test the ability of a material to withstand the effects of weather. These test chambers can measure variables such as humidity, ozone, and heat. The most common use of the weathering chambers is to test materials developed to endure external conditions. Another possibility for further research would be a study that focuses on the effect of humidity, ozone, and heat on the composition of latex inkjet inks.

The color gamut of a printing device is determined by the hue, saturation, and lightness of the inks used. Brightness, and other characteristics of the substrate used are also important in determining the color gamut of a printing device. In previous studies, the gamut size and volume comparison have been used to provide a visible and numerical representation of the change in the samples after exposure to light. Future research focused on gamut comparisons would provide a deeper understanding of how light affects the inks' permanence, stability, and total output capabilities.

Another possible direction for future research would be to adapt $L^*C^*h^*_{(ab)}$ color space to investigate lightfastness characteristics during analysis. Previous research indicates that inks generally fade from brighter to duller. ΔC^* would distinctly identify the color difference in chroma. Appendix A provides a starting point in this direction by displaying chroma values that have been calculated from the measurements taken using $L^*a^*b^*$ color space.

In addition to this, future research could examine fade or colorimetric shift in long exposures. It has been found that in some cases, the changes are more abrupt during the early stages of the exposure. It would also be interesting to apply more time intervals and a longer final exposure time used in these proposed studies.

Another possibility for future research is to conduct a study with an increased number of data points that would potentially provide a more accurate and significant analysis of the results. Future researchers could collect more data by repeating the methodologies used in the present study multiple times, as such, more information can be gained to inform the uncontrolled variation of the methods employed while providing sufficient data for parametric statistical analysis. As a result of the limited number of data points gathered from the samples in the present study, a non-parametric exact sign test was conducted to determine the significance of the differences in ΔE_{00} between water-based inkjet inks and latex-based inkjet inks, at 48 and 96 hours of exposure. The results are provided as a reference in Appendix B.

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Appendix A

Delta Chroma Calculations

	Before exposure	**After exposure**		**Before exposure**	**After exposure**	
Sample #	**C_1 48h**	**C_2 48h**	**ΔC**	**C_1 96h**	**C_2 96h**	**ΔC**
Substrate	7.28	3.83	3.45	7.28	0.90	6.37
Substrate	7.28	3.86	3.42	7.28	2.09	5.19
Substrate	7.07	3.84	3.23	7.07	1.37	5.71
Average			3.37			5.76
Cyan	47.63	44.76	2.87	47.63	43.84	3.79
Cyan	47.79	44.70	3.09	47.79	43.25	4.54
Cyan	47.77	43.03	4.74	47.77	44.30	3.47
Average			3.57			3.93
Magenta	65.12	61.69	3.43	65.12	61.27	3.86
Magenta	65.49	61.74	3.75	65.49	61.09	4.40
Magenta	65.30	61.70	3.60	65.30	60.94	4.36
Average			3.59			4.20
Yellow	61.09	59.99	1.10	61.09	59.18	1.91
Yellow	61.22	60.02	1.20	61.22	59.02	2.19
Yellow	60.61	59.95	0.66	60.61	58.49	2.13
Average			0.99			2.08
Black	7.92	7.13	0.78	7.92	7.03	0.89
Black	7.95	7.06	0.89	7.95	7.00	0.95
Black	7.97	7.09	0.88	7.97	7.09	0.88
Average			0.85			0.91

Table 4. Sample 1 difference in Chroma for each ink color on water-based inkjet ink.

	Before exposure	**After exposure**		**Before exposure**	**After exposure**	
Sample #	**C_1 48h**	**C_2 48h**	**ΔC**	**C_1 96h**	**C_2 96h**	**ΔC**
Substrate	7.28	3.17	4.11	7.28	2.09	5.19
Substrate	7.24	3.18	4.06	7.24	2.17	5.07
Substrate	7.52	3.31	4.21	7.52	2.14	5.38
Average			4.13			5.21
Cyan	47.79	44.97	2.81	47.79	43.25	4.54
Cyan	47.75	45.07	2.68	47.75	43.21	4.53
Cyan	47.94	45.08	2.86	47.94	43.37	4.57
Average			2.78			4.55
Magenta	65.40	60.87	4.53	65.40	61.09	4.31
Magenta	65.49	61.50	3.99	65.39	61.04	4.34
Magenta	65.17	61.00	4.17	65.24	60.74	4.51
Average			4.23			4.39
Yellow	61.22	59.88	1.34	61.22	59.02	2.19
Yellow	61.22	59.87	1.34	61.22	58.54	2.67
Yellow	61.17	59.70	1.47	61.17	58.79	2.38
Average			1.38			2.41
Black	7.92	7.06	0.85	7.92	7.00	0.92
Black	7.91	7.07	0.84	7.91	7.08	0.83
Black	8.02	7.14	0.87	8.02	7.06	0.95
Average			0.85			0.90

Table 5. Sample 2 difference in Chroma for each ink color on water-based inkjet ink.

	Before exposure	After exposure		Before exposure	After exposure	
Sample #	**C_1 48h**	**C_2 48h**	**ΔC**	**C_1 96h**	**C_2 96h**	**ΔC**
Substrate	7.07	3.38	3.69	7.07	1.37	5.71
Substrate	7.13	3.33	3.80	7.13	1.39	5.75
Substrate	7.17	3.27	3.90	7.17	1.34	5.83
Average			3.80			5.76
Cyan	47.77	45.43	2.34	47.77	44.30	3.47
Cyan	47.86	45.54	2.32	47.86	44.31	3.55
Cyan	47.85	45.60	2.25	47.85	44.33	3.52
Average			2.31			3.51
Magenta	65.30	61.60	3.70	65.30	60.94	4.36
Magenta	65.31	61.69	3.62	65.31	60.97	4.34
Magenta	65.35	61.69	3.66	65.35	60.93	4.43
Average			3.66			4.38
Yellow	60.57	59.45	1.12	60.57	58.49	2.09
Yellow	60.61	59.45	1.17	60.61	58.47	2.14
Yellow	60.56	59.47	1.09	60.56	58.50	2.06
Average			1.13			2.10
Black	7.90	6.86	1.04	7.90	6.79	1.12
Black	7.85	6.80	1.04	7.85	6.81	1.03
Black	7.89	6.76	1.13	7.89	6.78	1.11
Average			1.07			1.09

Table 6. Sample 3 difference in Chroma for each ink color on water-based inkjet ink.

	Before exposure	**After exposure**		**Before exposure**	**After exposure**	
Sample #	**C_1 48h**	**C_2 48h**	**ΔC**	**C_1 96h**	**C_2 96h**	**ΔC**
Substrate	7.33	2.53	4.80	7.33	1.22	6.11
Substrate	7.33	2.52	4.81	7.33	1.29	6.04
Substrate	7.30	2.44	4.86	7.30	1.25	6.05
Average			4.82			6.07
Cyan	55.72	55.20	0.52	55.72	54.62	1.10
Cyan	55.71	55.18	0.53	55.71	54.63	1.09
Cyan	55.77	55.21	0.57	55.77	54.60	1.18
Average			0.54			1.12
Magenta	69.32	68.26	1.06	69.32	68.00	1.32
Magenta	69.38	68.29	1.09	69.38	68.01	1.37
Magenta	69.30	68.25	1.05	69.30	68.00	1.30
Average			1.07			1.33
Yellow	76.49	76.31	0.17	76.49	75.18	1.31
Yellow	76.54	76.29	0.25	76.54	75.15	1.39
Yellow	76.46	76.37	0.10	76.46	75.11	1.36
Average			0.17			1.35
Black	1.45	1.75	-0.30	1.45	1.75	-0.31
Black	1.45	1.76	-0.31	1.45	1.79	-0.34
Black	1.46	1.76	-0.29	1.46	1.82	-0.36
Average			-0.30			-0.34

Table 7. Sample 1 difference in Chroma for each ink color on latex inkjet ink.

	Before exposure	**After exposure**		**Before exposure**	**After exposure**	
Sample #	**C_1 48h**	**C_2 48h**	**ΔC**	**C_1 96h**	**C_2 96h**	**ΔC**
Substrate	7.21	3.64	3.57	7.21	1.21	6.00
Substrate	7.23	3.67	3.56	7.23	1.25	5.98
Substrate	7.26	3.66	3.60	7.26	1.21	6.05
Average			3.58			6.01
Cyan	55.45	54.77	0.68	55.45	54.30	1.15
Cyan	55.49	54.72	0.76	55.49	54.30	1.19
Cyan	55.55	54.77	0.77	55.55	54.32	1.23
Average			0.74			1.19
Magenta	69.09	68.08	1.01	69.09	67.80	1.29
Magenta	69.02	68.14	0.88	69.02	67.81	1.21
Magenta	69.07	68.15	0.91	69.07	67.73	1.34
Average			0.94			1.28
Yellow	76.81	76.26	0.55	76.81	75.67	1.15
Yellow	76.78	76.32	0.46	76.78	75.60	1.18
Yellow	76.79	76.30	0.49	76.79	75.67	1.12
Average			0.50			1.15
Black	1.46	1.70	-0.24	1.46	1.76	-0.30
Black	1.44	1.70	-0.25	1.44	1.79	-0.34
Black	1.48	1.74	-0.26	1.48	1.80	-0.32
Average			-0.25			-0.32

Table 8. Sample 2 difference in Chroma for each ink color on latex inkjet ink.

	Before exposure	After exposure		Before exposure	After exposure	
Sample #	**C_1 48h**	**C_2 48h**	**ΔC**	**C_1 96h**	**C_2 96h**	**ΔC**
Substrate	7.27	2.23	5.05	7.27	1.03	6.25
Substrate	7.26	2.24	5.02	7.26	1.03	6.23
Substrate	7.28	2.20	5.07	7.28	1.08	6.19
Average			5.05			6.22
Cyan	55.76	54.95	0.82	55.76	54.48	1.29
Cyan	55.86	54.90	0.95	55.86	54.45	1.41
Cyan	55.79	54.99	0.80	55.79	54.48	1.30
Average			0.86			1.33
Magenta	69.25	68.27	0.97	69.25	67.90	1.34
Magenta	69.22	68.26	0.96	69.22	67.91	1.31
Magenta	69.28	68.34	0.94	69.28	67.86	1.42
Average			0.96			1.36
Yellow	76.63	76.30	0.34	76.63	75.66	0.97
Yellow	76.65	76.35	0.30	76.65	75.69	0.97
Yellow	76.61	76.29	0.32	76.61	75.61	1.00
Average			0.32			0.98
Black	1.56	1.67	-0.11	1.56	1.79	-0.23
Black	1.57	1.74	-0.17	1.57	1.86	-0.29
Black	1.57	1.69	-0.12	1.57	1.78	-0.21
Average			-0.13			-0.25

Table 9. Sample 3 difference in Chroma for each ink color on latex inkjet ink.

Appendix B

Statistical Analysis of Results

Given the limited number of data points in the present research, the non-parametric exact sign test was conducted to describe the significance of the differences in ΔE_{00} between water-based inkjet inks and latex-based inkjet inks, at 48 hours of exposure and at 96 hours of exposure.

Initial colorimetric measurements were taken, and ΔE_{00} values were calculated after exposure in the Q-Sun chamber to ascertain the lightfastness characteristics of the respective inks. Three readings were taken of each cyan, magenta, yellow, and black ink solids.

For these tests, the hypotheses are as follows:

H_0: median ΔE_{00} water-based ink = median ΔE_{00} latex-based ink

H_1: median ΔE_{00} water-based ink ≠ ΔE_{00} latex-based ink

An exact sign test was conducted to determine the lightfastness characteristics by type of ink at 48 hours of exposure. Typical water-based inkjet inks were compared to latex-based inkjet inks. Three readings were taken of each cyan, magenta, yellow, and black solids before and after exposure, and ΔE_{00} color difference values were calculated.

Of the 12 difference calculations after 48 hours of exposure, all samples of the latex-based inkjet inks exhibited increased lightfastness characteristics, as manifest by lower ΔE_{00} values. There was a statistically significant median decrease in ΔE_{00} (*Mdn* = 0.635) with the latex-based inkjet ink (*Mdn* = 0.51 ΔE_{00}) compared to the water-based inkjet ink (*Mdn* = 1.275 ΔE_{00}), $p < .001$.

In addition, an exact sign test was conducted to determine the lightfastness characteristics by type of ink at 96 hours of exposure. Typical water-based inkjet inks were compared to latex-based inkjet inks. Three readings were taken of each cyan, magenta, yellow, and black solids before and after exposure, and ΔE_{00} color difference values were calculated.

Of the 12 difference calculations after 96 hours of exposure, all samples of the latex-based inkjet inks exhibited increased lightfastness characteristics, as manifest by lower ΔE_{00} values. There was a statistically significant median decrease in ΔE_{00} (*Mdn* = 0.845) with the latex-based inkjet ink (*Mdn* = 0.74 ΔE_{00}) compared to the water-based inkjet ink (*Mdn* = 1.655 ΔE_{00}), $p < .001$.