Bruce Leigh Myers, Ph.D.

S T U D E N T W O R K

1.Lab Reports for Color Management / Tone and Color Course
In the Color Management and Tone and Color courses, students are required to edit and reformat prior lab reports to make them “portfolio pieces” that they can show in job interviews. They are also required to include their results of the Farnsworth Munsell 100 Hue Test.

2. Summative Written Assignment for Research Methods Course
In the graduate Research Methods course, students are required to write a properly cited, thematic literature review that leads to a meaningful research question that is feasible for an empirical degree culmination (thesis or capstone).

3. ISO-2846 Lab Report for Print Production Course
In the undergraduate Print Production course, students collect data required for ISO-2846 testing and are required to create a lab report showing their data and work.

4. Extracurricular: Technical Association of the Graphic Arts (TAGA) 2025 Student Competition, T-Shirt Category
Students designed, tie-dyed, and printed T-Shirts for the 2025 TAGA student competition.

5. Book Production for Lithographic Process Course
Students produced a book “Test Targets 11” as part of the undergraduate Lithographic Production course. The resulting book is comprised of student and faculty research, and students did all the premedia work, including proofing. The book was printed at a local commercial printer with the students in attendance, and bound at a local bindery, again with the students in attendance. This project was in addition to hands-on work in the materials laboratory where students evaluated substrates, inks, and fountain solution, as well as paper feeding, transport, delivery, and ink key adjustments using a small lithographic press on campus.

6. Kodak Trade Dress for Team Project Course
A team of students in the undergraduate Team Project course worked with marketing management personnel from Eastman Kodak Company for their trade dress: color cards for Kodak Red and Kodak Yellow that are distributed to printers producing Kodak-branded products.

7. Extracurricular: Italian Trade Agency Chicago USA: Italian Technology Award for the Graphic, Printing and Converting Industries - ACIMGA
In 2025, the ACIMGA approached RIT about a student paper writing contest which entaiiled students writing papers to win a trip to Italy. Over the course of six weeks, met with interested students to help with their writing and research, four students were selected to go on the trip in June, 2025.

1. L A B R E P O R T S

In the Color Management (undergraduate) and Tone and Color (graduate) courses, students are required to edit and reformat prior lab reports to make them "portfolio pieces" that they can show in job interviews. They are also required to include their results of the Farnsworth-Munsell 100 Hue Test. Following examples include:

- Colorimetric and Densitometric Analysis of Spot Colors
- Directional vs Sphere Geometry
- Empirical Selection of Scanner Gamma
- Farnsworth-Munsell 100 Hue Test Results

Lab 5 Colorimetric Vs. Densitometric Analysis of Spot Color

[redacted]

PPRT.602.01 - Tone and Color Analysis

Dr. Bruce Myers

28 November, 2022

Introduction

In this lab, colorimetric and densitometric values of two green spot color solid patches (#19 and #20) will be measured by TECHKON Densitometer. These two patches are printed on gloss paper. The purpose this lab is to compare colorimetric and densitometric values of two spot color patches.

Materials

- TECHKON Densitometer (Serial number: B704049)
- Spot color patches

Procedure

- Calibrate the TECHKON densitometer
- Measure L*a*b* the two green patches separately and make sure the measurement is in D50/2 degrees M0. Record the colorimetric values from the TECHKON.
- Measure the CMYK density of the two green patches separately and make sure the measurement is in Status-T, Unpolarized, and Absolute. Record the densitometric values from the TECHKON.
- Use the collected data to calculate the ΔE_{76}, hue error, and grayness values

Data

Table 1

Colorimetric and ΔE Values of #19 and #20 Patch

Colorimetric Value	#19	#20
L*	40.93	41.08
a*	-14.11	-15.83
b*	20.86	19.33
C (Chroma Line)	25.11	25.09
h (Hue Angle)	123.98	129.25
ΔE_{76}	2.31	

Note. Colorimetric values are measured in D50/2° MO

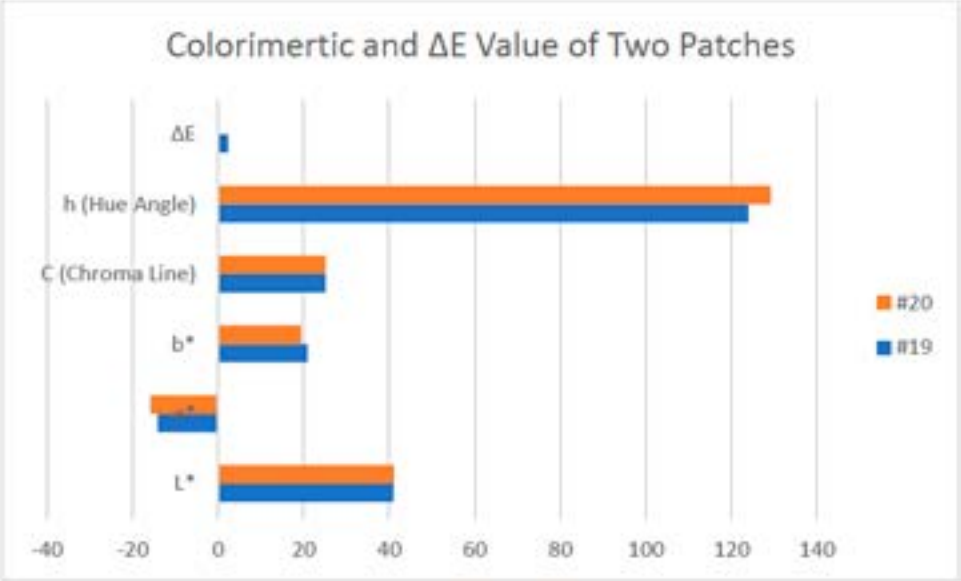


Figure 1. Comparison of Colorimetric values of #19 and #20

Table 2

Densitometric Value of #19 and #20 Patch

Densiometric	#19	#20
Cyan	1	1.06
Magenta	0.85	0.88
Yellow	1.09	1.19
Black	0.94	0.94
Grayness	77.98	73.95
Hue error	50	38.71

Note. Densitometric values are measured in Status-T, Unpolarized and Absolute

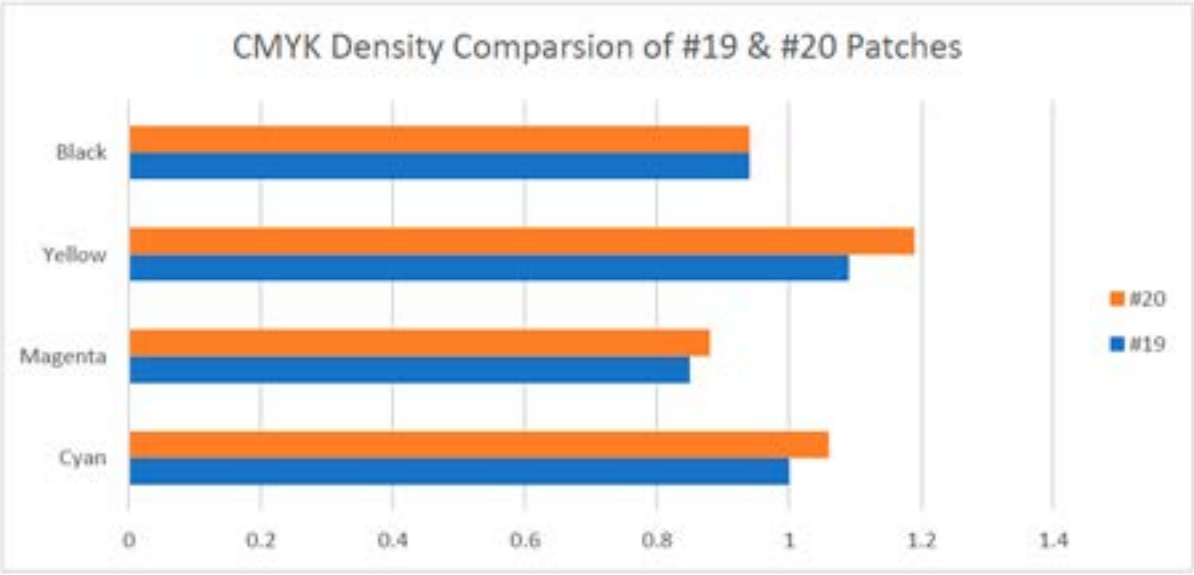


Figure 2. Comparison of Density Values of #19 and #20 Patches

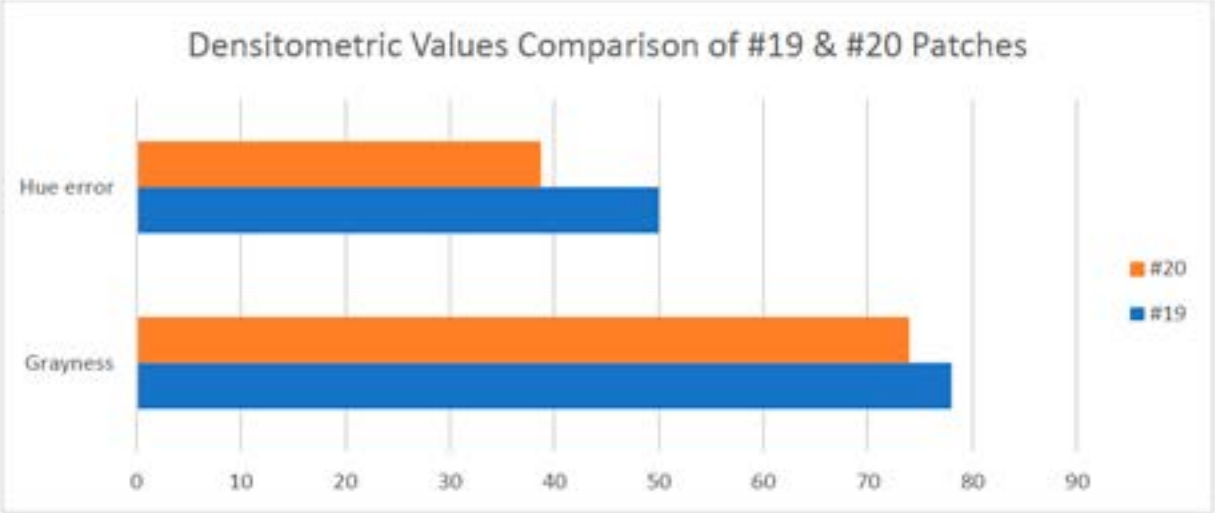


Figure 3. Comparison of Hue error and Grayness Values of #19 and #20 Patches

Summary

The densitometric and colorimetric values of two spot color patches (#19 and #20) will be measured by TECHKON densitometer to compare the color difference between patches. Densitometric values are measure in Status-T, Unpolarized, Absolute and colorimetric values are measure in D50/2 degrees M0. The data of the densitometer and colorimetric values are shown above.

For the colorimetric values, ΔE76 of two patches are 2.31. According to Figure 1, these two patches' Chroma line (C) and lightness (L*) values are almost identical. #20 patch has a higher value than #19 in a* and h (Hue Angle). #19 patch has a higher value than #20 patch in b*. According to Figure 2, the black density of these two patches is almost the same for densitometric values. #20 patch have higher density values in Cyan, Magenta, and Yellow. According to Figure 3, the #19 patch has a higher hue error and grayness value.

Analysis

In the CIE Lab and LCH model, color can define by five values. L* is lightness, a* is the red-green component (positive 'a*' is red and negative 'a*' is green), b* is the yellow-blue component (positive 'b*' is yellow and negative 'b*' is blue), C is the Chroma line, and h is the hue angle (Ashe, 2014). In this lab,

colorimetric values are measured in D50/2 ° M0. Since ΔE76 of two patches are 2.31, it could conclude that #19 and #20 provide two different color appearances under the lab measurement condition (D50/2°M0). #19 and #20 have similar L* and C values, meaning these color patches display similar lightness and saturation. Compared to a*, b*, and H values of these two patches in the CIE Color Space Guide from X-Rite, #20 patch contains a more greenish color and is closer to the blue axis, and #19 contains a more yellowish color. Hue error indicates the variation from a theoretically perfect or ideal cyan, magenta, or yellow. Grayness indicates the gray component of a color (X-Rite, 2003). Since the #19 patch contains higher values in Hue error and grayness, it provides a more gray and brownish appearance.

Reference

Ashe, T. (2014). Color Management & Quality Output: Mastering Color from camera to display to print. Focal Press.

X-Rite. (2003). A Guide to Understanding Graphic Arts Densitometry. Retrieved October 2, 2022, from https://www.xrite.com/-/media/xrite/files/whitepaper_pdfs/l10-001_a_guide_to_understanding_color_communication/l10-001_understand_color_en.pdf.

Lab 8 Directional vs. Spherical Instrument Geometry

[redacted]

PPRT.602.01 - Tone and Color Analysis

Dr. Bruce Myers

28 November, 2022

8.1 Visual Color Difference

8.1.1

Directional Instrument model and serial number: TECHKON (#B704049)

Parameters for directional Instrument readings: D50/2° M0

Spherical Instrument model and serial number: X-Rite SP62

Parameters for spherical Instrument readings: D65/10° SPIN

8.1.2

Table 1

Colorimetric Values of Orange Side "Target Tolerance" Sheet.

	Light	Dark	Red	Green	Yellow	Blue	Range
ΔE_{76}	2.3	3.2	2.0	1.9	1.3	2.4	1.9
$\Delta E_{cmc(2:1)}$	0.89	1.24	1.17	0.89	0.68	1.25	0.57

Note: ΔE_{76} values are measured by TECHKON and $\Delta E_{cmc(2:1)}$ are measured by X-Rite SP62. The parameters for TECHKON reading are: D50/2° M0. The parameters for X-Rite SP 62 reading are: D65/10° SPIN

From Table 1, the range of color difference from TECHKON is more than twice more significant than the X-Rite. Several factors cause the distinct result of the color difference values. The differences are shown below:

- Measure instruments geometry
- Illuminant
- The equation of calculating the ΔE

Even though following the measure requirement on the "Target Tolerance" sheet, the results of the ΔEcmc do not fulfill the "one ΔEcmc" color difference requirement on the sheet. Therefore, the visual color analysis showed one ΔEcmc difference, but the measured data were not. Compared to the ΔE76 and ΔEcmc values, the ΔEcmc are closer to the "one ΔEcmc" color difference requirement. This lab indicates that following the SOP (Standard Operating Procedure) on the measurement target is critical

during the measurement. Also, ensure the employees and trainees have been trained and follow the measurement instruments' instructions. Otherwise, the measured result will not be correct and will affect the products and manufactory quality.

8.2 Gloss and Foil Analysis

Directional Instrument model and serial number: X-Rite eXact

Parameters for directional Instrument readings: D50/2° M0

Spherical Instrument model and serial number: X-Rite SP62

Parameters for spherical Instrument readings: D65/10°

Gloss Sample

Table 1

Colorimetric Values of Gloss Sample Measured by Directional Instrument

	5	20	40	60	80	Range
L*	16.34	6.25	3.54	3.02	1.98	14.36
a*	-0.31	-0.32	-0.32	-0.3	0.03	0.35
b*	-1.23	-0.2	0.29	0.43	0.31	1.66
C*	1.46	0.75	0.07	0.29	0.22	1.39
h_{ab}	260	250.58	248.32	226.82	276.57	49.75

Note. Colorimetric values measured by X-Rite eXact. The parameters for X-Rite eXact reading are: D50/2° M0.

Table 2

Colorimetric Values of Gloss Sample Measured by Spherical Instrument

	5	20	40	60	80	Range
L*	26.08	26.37	26.09	26.29	25.57	0.8
a*	-0.16	-0.3	-0.38	-0.41	-0.06	0.35
b*	-1.18	-1.29	-1.15	-1.09	-0.29	1
C*	1.15	1.35	1.25	1.11	0.31	1.04
h_{ab}	262	256.8	252.2	248.8	257	13.2

Note. Colorimetric values measured by X-Rite SP62 (SPIN). The parameters for X-Rite SP62 reading are: D65/10°.

Table 3

Colorimetric Values of Gloss Sample Using Spherical Instrument

	5	20	40	60	80	Range
L*	24.47	20.25	16.28	12.24	7.21	17.26
a*	-0.15	-0.3	-0.31	-0.33	-0.05	0.28
b*	-1.17	-1.42	-1.33	-1.57	-1.75	0.58
C*	1.2	1.51	1.44	1.53	2.01	0.81
h_{ab}	263.2	260.3	259.1	256.5	268.2	11.7

Note. Colorimetric values measured by X-Rite SP62 (SPEX). The parameters for X-Rite SP62 reading are: D65/10°.

According to the visual analysis of the gloss sample, it is hard to tell the difference between 20 to 60 color blocks with the glossy effect at first glance. The sample will display a more apparent color difference between each block when it is viewed from a certain angle. There is a dramatic change in the L* value range during these three measure conditions. The L* value range is the smallest when it measures with a spherical densitometer (X-Rite SP62) with the specular component included. According to the explanation about the SPIN and SPEX on the X-Rite website, "Measuring Specular Included negates the effect of surface appearance to measure only color, similar to how the human eyes would see the magazine picture without the gloss reflection." Also, "Measuring Specular Excluded (SPEX) – aka Specular Component Excluded (SCE) – is similar to how your eye perceives color in that the surface characteristics become part of the color you see." (Tim, 2021). Therefore, under the SPIN mode, the instrument will take out the gloss effect from the paper, and the L* value will not have too many changes from the lightest to the darkest color block, which makes the L* range small.

Comparing data between the directional instrument (X-Rite eXact) and to spherical densitometer (X-Rite SP62), the hue angle ranges from the X-Rite eXact is the most significant value than the other two. The directional instrument will remove the gloss from the measurement and measure the appearance of the sample exactly as the human eye would see it (X-Rite, 2013). Therefore, the hue angle measured by the directional instrument is the largest.

Foil Sample

Table 1

Colorimetric Values of The Foil Sample Measured by Directional Instrument

L*	25.9
a*	-5.69
b*	-18.81
C*	19.73
h_{ab}	253.37

Note. Colorimetric values measured by X-Rite eXact. The parameters for X-Rite eXact reading are: D50/2° M0.

Table 2

Colorimetric Values of The Foil Sample Measured by Spherical Instrument

L*	83.47
a*	-31.63
b*	-8.19
C*	32.54
h_{ab}	194.6

Note. Colorimetric values measured by X-Rite SP62 (SPIN). The parameters for X-Rite SP62 reading are: D65/10°.

Table 3

Colorimetric Values of The Foil Sample Measured by Spherical Instrument

L*	77.96
a*	-29.7
b*	-8.8
C*	30.92
h_{ab}	196.5

Note. Colorimetric values measured by X-Rite SP62 (SPEX). The parameters for X-Rite SP62 reading are: D65/10°

In this lab, the bluish side of the foil sample has been measured. The bluish side of the sample has a shiny and metal color under the light. Also, the sample has texture on the surface. The above shows the colorimetric data collected by a directional instrument (X-Rite eXact) and spherical instrument (X-Rite SP62) with SPIN or SPEX. The data from the spherical instrument (Table 6, 7) have a similar value on the colorimetric variables, and the data from the directional instrument has a big difference from the spherical. The substrate material and texture will influence the colorimetric values

depending on the instrument geometry. A spherical densitometer can include the "specular component," while measuring and color formulation are more accurate when this component is included (X-Rite, 2016). Since the sample has a gloss and textured surface, the data from a spherical densitometer with a specular component will be more accurate.

Reference

Mouw, T. (2021, March 30). *Spin or Spex: Which is best for Gloss Measurement?: X-rite blog*. SPIN or SPEX: Which is Best for Gloss Measurement? Retrieved October 8, 2022, from https://www.xrite.com/blog/specular-included-or-specular-excluded-which-is-best

X-Rite. (2016). *A Guide to Understanding Color Communication*. Retrieved October 2, 2022, from https://www.xrite.com/-/media/xrite/files/whitepaper_pdfs/l10-001_a_guide_to_understanding_color_communication/l10-001_understand_color_en.pdf.

Lab 12 Empirical Selection of Scanner Gamma

[redacted]

PPRT 602.01 Tone and Color Analysis

Dr. Bruce Myers

5 November, 2022

Introduction

The purpose of this lab is to use SilverFast software to find the minimizing average ΔE value for the IT8 scanning profile. In order to create a scanner profile to achieve the color management goal, it is essential to have a low ΔE value of IT8 scans. Therefore, changing different values of the gamma gradation in SilverFast software will find the lowest average ΔE value for the calibrated IT8 target.

Material

- IT8 target
- Epson 10000XL
- SilverFast software

Procedure

- Place the IT8 target in the Epson 10000XL.
- Open the SilverFast software to change and record the value of gamma gradation.
- Use the IT8 calibration process in SilverFast to scan the IT8.
- Record the average ΔE value from the IT8 calibration process.
- Change the gamma gradation value until it finds the lowest average ΔE value.

Data

Table 1

Values of Gamma Graduation and Average ΔE Value

Gamma Gradation	Average ΔE Value
1.9	0.9
2	0.8
2.1	0.8
2.2	0.8
2.3	0.8
2.4	0.8
2.5	0.9

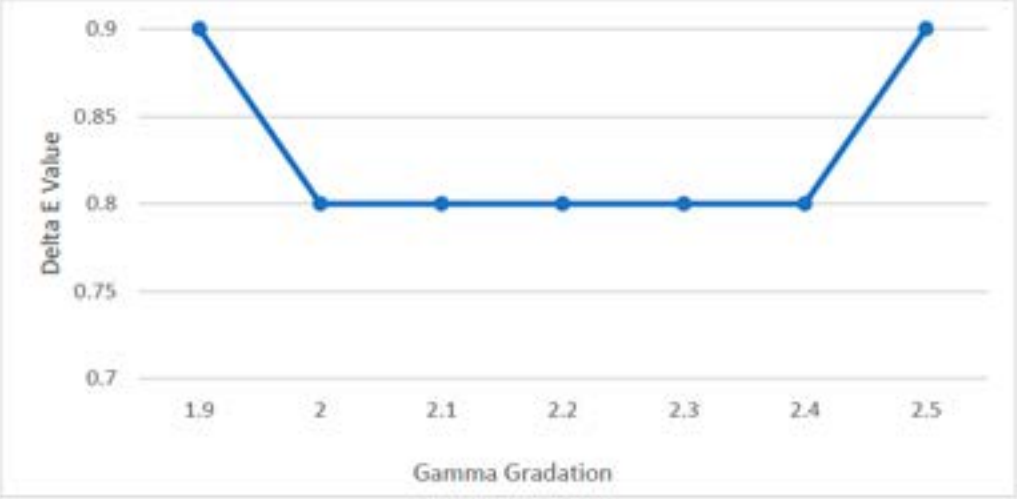


Figure 1. Curve of the gamma graduation and average ΔE value

Conclusion

Creating consistently color-accurate printing is essential for the print industry. Scanners with a profile produce more accurate color than those without a profile (Adams & Ollagnier, 1998, pp. 4, 6). The method to create a profile in this lab is scanning an IT8 target using an Epson 10000XL scanner. After scanning the IT8 target, SilverFast software provides an IT8 scan calibration.

During the IT8 calibration process, changing the different gamma graduation value of the IT8 scans affect the value of average ΔE. The lowest ΔE value of the IT8 scans means it achieves optimal color reproduction. The default gamma graduation in the SilverFast software is 2.2. In Table 1, the

lowest ΔE value is 0.8, and the corresponding gamma gradation value is between 2 to 2.4. Figure1 shows the relationship between gamma gradation and ΔE value. When the gamma gradation value is between 2 to 2.4, the ΔE value will be the lowest, and gamma 2.2 is the optimal value for the IT8 target scan calibration.

Analysis

Color management uses software to provide consistent and optimal color reproduction from one output device to another. Profiles created by color management programs for the device can provide a more accurate color reproduction. To create a profile for the scanner, scanning an IT8 scan with calibration can provide better color reproduction than without calibration. The purpose of this lab is going to figure out the lowest ΔE value during the calibration and its corresponding gamma gradation.

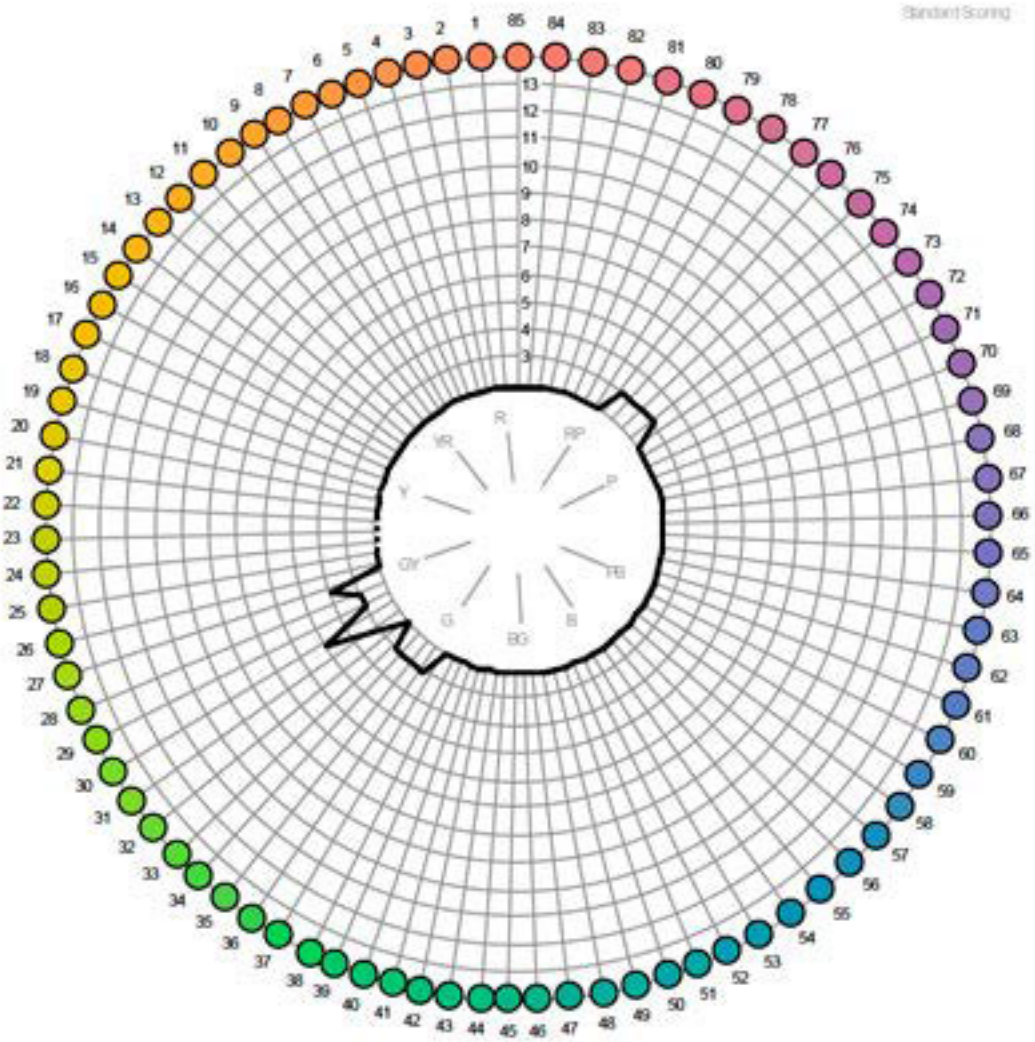
ΔE value refers to the overall color difference between an original IT8 target and its reproduction scans. The lowest ΔE value it can achieve, the better color reproduction it can provide for devices. According to the SilverFast manual, gamma gradation adjusts the general brightness of the image for mid-tone and shadow. (Karl-Heinz & Gerhard, 2010, p. 55) Scans with high gamma values will have a lighter appearance and more detail in the dark area than low gamma scans. In this lab, the default gamma gradation is 2.2, the default for Apple computers. This experiment records the corresponding ΔE value of gamma 2.2 ± 0.3. The result shows that the lowest ΔE value locates on gamma 2.2. Therefore, the gamma value should be set between 2 to 2.4 during the scanning to achieve better color reproduction for IT8 scans and an IT8 profile.

Reference

Adams, R. M., & Ollagnier, L. M. (1997, July 1). Scanner Profiling Software for Color Management. *Graphic Arts Technical Foundation*, *63*, 2-9.

Zahorsky, K. H., & Wolff, G. (2010, February 10). SilverFast Manual. SilverFast Manual. Retrieved November 2, 2022, from https://www.silverfast.com/download/docu/manual,complete_en_2006-11-27.pdf

Farnsworth-Munsell 100 Hue Test Results



Total Error Score (TES): 16 Classification: Superior Discrimination Subject: [redacted] Reference: Date of Birth: Date of Test: 10/18/2022 Test Duration: (mins) Gender: Unspecified Geographic Location:Unspecified Industry Type: Unspecified Primary Job Function: Unspecified Years of Experience: Unspecified Illumination Type: D65	Test Serial Number: Cap Order: 85, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 30, 28, 29, 31, 32, 33, 35, 34, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 76, 75, 77, 78, 79, 80, 81, 82, 83, 84 FM 100 hue test results not certified (No Serial Number). Comments:

Test produced by:
Munsell Color Services Laboratory
X-Rite Inc
Kentwood, MI

2. LITERATURE REVIEW

In the graduate Research Methods course, students are required to write a properly cited, thematic literature review that leads to a meaningful research question that is feasible for an empirical degree culmination (thesis or capstone). An example follows.

[redacted]

GRCS.701

Summative Assignment

Background

In the United States, healthcare facilities generate approximately 14,000 tons of total waste per day, and roughly 20–25% of that is plastic (Rizan, C. et al, 2020). Recent analyses estimate that U.S. and Canadian healthcare systems produced around 1.2 million metric tons of single-use healthcare plastic waste in 2023, with less than 5% recycled. Manufacturers and hospitals alike are under constant pressure to reduce their environmental impact while maintaining the required sterilization and ensuring patient safety. One of the main causes for healthcare producing this amount of waste is the packaging. Part of the challenge is how the industry is restricted to a "make-use-dispose" or "one-use" model. Meaning that a majority of medical devices and packaging are meant to be used once and then thrown away, instead of being cleaned, sterilised, and used again in a circular system. Therefore, most of the packaging waste will be landfilled or incinerated. The composition of this waste is dominated by polypropylene (PP), polyethene (PE), and PVC, often found in IV bags, syringes, catheter sets, and sterile packaging within operating rooms or intensive care units (Rizan et al., 2022). Despite the notion of the healthcare environment being "clean", the main reason a majority of the plastic waste generated is not recycled is because of infection control restrictions. Packaging choices will influence greenhouse gas emissions, resource use, sterilization energy requirements, and end-of-life outcomes.

There is a perception that replacing conventional medical packaging materials with paper or biopolymer alternatives will reduce environmental impact. However, there is also a perception that these alternative materials do not meet the same standards of sterilization and safety. Optimal performance depends on various factors, including life-cycle stages, durability, and barrier properties. If an eco-friendly packaging fails prematurely, it will only generate more waste and invalidate the proposed benefits. For years, polymer materials, such as Tyvek, have been the standard for sterile barriers due to their excellent properties and compatibility with various sterilization methods. Various life-cycle assessments showcase that healthcare plastics cause impacts at multiple stages: fossil fuel extraction, polymer production, manufacturing, transportation, and end-of-life incineration or landfill. A slight change in one of these stages can have an overall positive environmental impact. For instance, segregation and recycling of medical device packaging can reduce environmental impact by a factor of nearly eight compared to incineration (Cho et al., 2024).

Even though a lot of these studies prove the negative effects of the current plastic packaging used in the medical industry, it is and will be very challenging to replace them. One of the main reasons it proves to be so difficult is the importance of the Sterile Barrier System (SBS). A sterile barrier system (SBS) is the packaging system that allows a medical device to be sterilised, provides a microbial barrier to maintain sterility, and permits aseptic presentation at the point of use. This relevance and significance make them a cornerstone of patient safety and infection prevention. It is crucial to monitor and ensure the integrity of the SBS because even a minor breach can compromise sterility and increase the chances of surgical infections. SBS materials must resist the admission of microbes, withstand various sterilization processes,

maintain seal strength, and retain overall integrity throughout distribution, storage, and handling. Because plastic-based materials have been engineered over decades to meet these stringent criteria reliably, many proposed alternative materials currently fall short in barrier performance or sterilization compatibility (van Doornmalen et al., 2020). Despite the environmental concerns, SBS remains difficult to replace in the healthcare industry due to its ability to provide consistent and validated sterility needed in medical devices to guarantee the patient's safety.

Sterilization is one of the most crucial factors in medical device manufacturing, providing product safety and the elimination of viable microorganisms. For decades, the industry has relied almost entirely on methods like Ethylene Oxide (EtO), steam autoclave, and gamma radiation. Conventional sterilization methods, like those mentioned above, have been around since the 1950s. Given the long period of time they have been in use, the research on the effects they have on packaging materials is extensive and is supported by decades of regulatory precedent. Building on this research, a list of packaging materials and their compatible sterilization process has been well established, streamlining the selection process of packaging materials for medical device manufacturers. Ethylene oxide (EtO) sterilization is one of the most widely used methods for medical devices because it can sterilize heat-sensitive, moisture-sensitive, and complex polymer-based products that cannot withstand steam or radiation sterilization. Studies show that alternative sterilization technologies struggle to achieve similar penetration and sterility assurance in devices with sharp internal channels, further reinforcing EtO’s dominance (Björkholm et al., 2018). Another factor important to evaluate is the material compatibility with the selected sterilization method. For example, EtO requires a porous material that allows the gas

to diffuse into and out of the package. Research exposes that incompatible packaging materials can lead to incomplete sterilization or retention of harmful EtO residues (Schmidt et al., 2017).

Due to all of the environmental issues discussed, the medical packaging sector has experienced increasing pressure to reduce reliance on conventional plastics. As a result, paper-based laminates, molded fiber, and biopolymer films derived from renewable resources have gained attention as potential replacements for petroleum-based polymers. All of these alternatives are attractive because they are capable of reducing carbon emissions and can align with circular-economy goals. Biopolymers, such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and cellulose-based composites, have become particularly prominent. A big part of their surge is due to biodegradability and their capability to be sourced from agricultural or microbial processes. As mentioned before, these advances are exciting but not entirely convincing due to sterilization tolerance and long-term material stability. Nevertheless, continued advancements in coating technologies, fiber engineering, and bio-derived barrier layers prove that sustainable packaging solutions are becoming increasingly feasible (Prieto, 2016).

Regardless of the growing interest in sustainable packaging for medical devices, there remains a significant lack of performance data regarding how biopolymer-based materials respond to common sterilization methods. Traditional medical packaging materials, such as polyethylene, polypropylene, and Tyvek, have decades of validated performance data demonstrating predictable mechanical behavior, barrier integrity, and stability across sterilization processes. In contrast, biopolymers such as PLA, PHA, and cellulose composites exhibit

different thermal, mechanical, and moisture sensitivity, yet comprehensive sterilization performance profiles are somewhat nonexistent. Various biopolymers show signs of degradation, a change in crystallinity, and a loss of mechanical strength when exposed to sterilization processes, but these conclusions are based on small-scale material performance, instead of full pouch performance evaluations (Farah et al., 2016). This data gap exposes an obstacle for integrating biopolymer pouches into Sterile Barrier Systems (SBS), because packaging materials must demonstrate consistent microbial barrier performance, seal integrity, and post-sterilization stability to meet regulatory requirements.

As sustainability pressures push the industry toward alternative materials, the limited evidence underscores the need for further research focused specifically on sterilization-ready biopolymer SBS components (Niaounakis, 2020). Overall, while the medical packaging industry faces increasing pressure to transition toward sustainable materials, the shift remains constrained by the lack of validated performance data for biopolymer-based sterile barrier components. Within emerging alternatives, PLA/PBAT blends have gained significant attention due to their balanced mechanical properties, improved flexibility, and better resistance to processing stresses compared to pure PLA. Studies show that adding PBAT to PLA can enhance ductility, reduce brittleness, and allow for improved heat-sealing behaviour (Jorda-Reolid et al., 2020). All of these characteristics are essential for creating functional medical pouches. Early research suggests that these blends may offer a viable pathway toward biopolymer packaging solutions that meet SBS requirements.

Literature Review

After introducing the broader context of medical packaging sustainability, the literature review examines the most relevant peer-reviewed studies that inform this research. It begins by reviewing research on the performance of conventional polymer-based sterile barrier systems, then turns to emerging biopolymer and paper-based alternatives, and finally considers studies evaluating the effects of sterilization processes on material integrity and sterile barrier performance.

Performance of Conventional Polymer-Based Sterile Barrier Systems

Conventional polymer-based sterile barrier systems (SBS) have served as the cornerstone of medical device packaging for several decades. These conventional materials offer a combination of microbial protection, mechanical strength, and sterilization compatibility that emerging sustainable alternatives have not completely matched. To fully understand the dominance these materials have in the industry, it is important to examine both their material properties as well as analyze the extensive data validating their overall performance. Throughout multiple studies and research efforts, clear benchmarks have been established to evaluate the feasibility of substituting polymer-based SBS with biopolymer materials.

van Doornmalen et al. (2020) provide one of the most detailed examinations of SBS requirements and performance. Their research is essential for understanding the regulatory landscape that emerging materials must enter and overcome. Their review emphasizes a factor that might go overlooked by most: SBS functionality is not determined by raw materials performance, but by the performance of the packaging system as a whole. This means it is

important to review seal strength, sterilization compatibility, handling stresses, and package integrity. One of their main focuses is the analysis of sunbonded HDPE (Tyvek). It is considered to be the gold standard for medical sterile barrier systems due to its unique material structure. The randomly oriented HDPE fiber network creates a highly porous path that prevents microbial ingress while still allowing sterilant penetration. This characteristic porousity is essential for the EtO sterilization process to be successful. van Doornmalen et al. (2020) also highlight common failure modes and explain the rigorous validation test required to demonstrate long-term sterility assurance. Some of the validation tests highlighted include dye penetration, burst testing, microbial challenge, and accelerated aging. The paper also discusses sterility assurance levels (SAL) and acceptable test thresholds, giving a regulatory and quantitative context that frames how evidence for material substitution must be gathered. Their findings show why conventional polymer materials remain the clinical standard: they have decades of proven performance across all SBS validation criteria, whereas many alternative materials have only been evaluated at the film level without system-level testing.

The authors note that polymer matrices can be engineered to present minimal variability in production batches, reducing the need for extensive per-batch validation that might be required for natural-fiber alternatives. Moreover, the review reveals that decades of industrial experience have calibrated not only material formulations but also processing windows that together deliver predictable performance. The processing windows can include heat-sealing temperatures and dwell times. Dwell time means the time spent o the same stage of a process. For any researcher or manufacturer aiming to replace conventional SBS, van Doornmalen et al.'s

exposition functions as a checklist: a set of quantifiable, system-level properties and validation expectations that must be satisfied.

While van Doornmalen et al. (2020) focus primarily on SBS engineering and performance, Rizan et al. (2022) address the broader environmental context in which these materials exist. Their assessment of healthcare plastic waste situates polymer SBS within a sustainability crisis. Their research notes that healthcare facilities in the U.S. and Canada generate substantial volumes of polypropylene (PP), polyethylene (PE), and PVC waste each year. Their research estimates that less than 5% of the waste produced is recycled. It is important to highlight that these materials are not chosen time and time again only because of their favorable properties, but also because they are integrated into device workflows and regulatory approvals. A main contribution of Rizan et al. (2022) is the clear clarification of end-of-life outcomes for a majority of medical packaging. A lot of the medical packaging is considered to be potentially infectious after use and, therefore, is destined for incineration instead of recycling.

Rizan et al. (2022) argue that this institutional integration further complicates transitions to sustainable alternatives, even as environmental pressures intensify. Additionally, their findings add to the conclusion made by van Doornmalen et al. (2020): the reason polymer SBS persists is not only convenience and familiarity, but the presence of a strong, validated performance that satisfies sterility and patient-safety requirements. Moreover, the environmental analysis performed by Rizan et al. strengthens the case for developing biopolymer SBS. However, it is important to mention that they also point out that sustainability efforts cannot compromise

microbial barrier performance. Thus, Rizan et al. provide a practical roadmap: reduce waste via systems improvements now and pursue validated material alternatives concurrently.

Whereas the first two studies establish the performance expectations and sustainability imperatives surrounding SBS materials, Björkholm et al. (2018) provide experimental evidence showcasing why conventional polymers continue to outperform alternatives in sterilization environments. Their work focuses on EtO sterilization, which is the dominant sterilization process, and exposes how different polymer-based materials behave after being exposed to the EtO process. The research shows that spun-bonded HDPE and multilayer polymer films retain seal strength, microbial barrier effectiveness, and show stable mechanical performance after exposure to EtO sterilization. All of the properties mentioned are essential, given that sterilization-compatible packaging must allow enough gas penetration to achieve sterility while also allowing for complete aeration to remove toxic residues. Björkholm et al. (2018) also reveal that sterilization efficacy is influenced not only by material chemistry but by device geometry and packaging configuration. Such findings highlight that sterilization compatibility is a systems-level phenomenon, aligning with the perspective presented by van Doornmalen et al. (2020).

Beyond EtO, the authors examine gamma irradiation effects. They document that while ionising radiation induces oxidative chain scission in many polymers, design choices can preserve mechanical and barrier properties after being exposed to the typical sterilization doses. For example, materials such as polyethylene and polypropylene display fair, predictable changes in tensile properties after gamma exposure but retain seal strength and microbial barrier

properties within acceptable validation limits. On the other hand, cellulose-based materials show severe loss of mechanical integrity or dimensional stability under similar doses. Meaning that without some added engineering, they are not suitable for radiation sterilization. Importantly, Björkholm et al. (2018) evaluate sterilization outcomes not only at the film level but within representative package geometries and device loads. Their results demonstrate that sterilant penetration and microbial inactivation depend heavily on pack configuration and loading density. All of these factors interact with material properties to determine clinical sterility. As mentioned before, a material that performs well as a flat film in laboratory tests may fail when formed into a pouch containing intricate devices. It can be concluded that sterilization compatibility is a decisive gatekeeper for SBS alternatives (Björkholm et al., 2018).

Taken together, these three studies form a coherent picture of why polymer-based SBS materials have remained the number one option in healthcare packaging. These three studies set the technical, regulatory, and sustainability context for investigating biopolymer and paper-based substitutes. Such research must provide package-level validation across sterilization processes while also offering credible lifecycle benefits.

Emerging Biopolymer and Paper-Based Materials for Medical Packaging

Recent years have seen growing interest in biodegradable polymers and cellulose-based materials as potential sustainable alternatives to conventional polymer-based materials for medical packaging. This interest is driven not only by environmental pressures but also by advances in polymer science that aim to overcome past limitations of biopolymers like brittleness, poor barrier properties, and sterilization incompatibility. Farah et al. (2016) deliver a

comprehensive review of PLA, summarizing different research efforts on its chemical, physical, and mechanical properties. They especially focus on how these characteristics influence their potential for packaging applications. This type of analysis is fundamental for the understanding of PLA's leading candidacy for medical packaging among other biopolymers. PLA has become extremely popular because it offers several attractive advantages. For example, it is derived from renewable sources, uses lower energy to produce, and it is processable through thermoplastic methods like extrusion molding (Farah et al., 2016). On the mechanical side, semi-crystalline PLA exhibits tensile strength and modulus comparable to some conventional plastics. These are important properties in medical packaging. However, there are critical limitations that might interfere with PLA's suitability for flexible packaging or SBS pouches. These limitations include PLA's brittleness at room temperature, limited toughness, and sensitivity to thermal and hydrolytic degradation (Farah et al., 2016).

Farah et al. describe multiple strategies to address these weaknesses. Some strategies include plasticization, chain extension, copolymerization, and blending with ductile polymers such as PBAT. Most of these improvements have been proven at the film or sample scale. In the context of SBS research, Farah et al. (2016) outline both the promise and the fundamental gaps that must be addressed before PLA-based materials can perform reliably. One of the most promising engineering approaches discussed in the literature involves blending PLA with PBAT to compensate for PLA's brittleness. Studies on PLA/PBAT blends demonstrate that such mixtures improve flexibility, toughness, and heat-sealability. However, PLA/PBAT blends still lack published data on package sealing performance and post-sterilization dimensional stability.

Caputo et al. (2024) conducted a computational and experimental investigation to evaluate how starch reinforcement influences the mechanical and chemical behavior of PLA/PBAT blends. Caputo et al. (2024) approached this reinforcement in the blends through starch addition combined with molecular-dynamics insight and experimental validation. Furthermore, the simulations demonstrated that starch molecules interact strongly with PLA segments while also moderating contact with PBAT, suggesting that starch behaves not only as a filler but also as a partial compatibilizer. Given the simulations, there is an expected increase in Young's modulus and shifting glass transition behavior (Caputo et al., 2024). These outcomes are great for packaging applications, given that there is an improvement in stiffness and handling performance. Importantly, the authors showed that starch addition reduces the size of PBAT dispersed domains and improves interfacial adhesion. This discovery directly translates to improved mechanical performance.

One of the most significant contributions of the study is its integration of simulation and experiment. The molecular modeling explains how hydrogen bonding and surface interactions between starch and PLA chains reduce interfacial tension in the blend. These findings explain why the reinforced materials exhibit improved mechanical uniformity and weak interfacial regions. It is important to note that these properties usually compromise sterile barrier integrity in medical packaging. Additionally, Caputo et al. highlight the environmental advantages of using starch as a low-cost, biodegradable reinforcement. Aligning perfectly to decrease waste in the healthcare industry. Overall, the work by Caputo et al. (2024) demonstrates that starch reinforcement offers a real method to enhance stiffness, interfacial adhesion, and structural integrity in PLA/PBAT blends. Their findings provide a scientific pathway for developing

stronger, more sustainable sterile-barrier packaging systems. Always as long as the improved ductility requirements are balanced with reinforcement levels.

Wang et al. (2020) investigated the compatibility of PLA/PBAT blends enhanced with an epoxy-terminated branched polymer (ETBP) as a reactive compatibilizer. This was done looking to address one of the primary limitations of PLA/PBAT systems: the complicated immiscibility. Immiscibility is the property of two or more liquids that are unable to completely blend. In this study, ETBP acts through chemical micro-crosslinking at the PLA–PBAT interface. The addition of ETBP is to promote improved interfacial adhesion and alter phase morphology (Wang et al.,2020). Using different tests like tensile testing, differential scanning calorimetry, dynamic mechanical analysis, and scanning electron microscopy (SEM), the authors demonstrated that ETBP significantly enhances toughness. To quote a specific result from the study, elongation at break increased from approximately 46% in the unmodified blend to more than 270% with 3.0 phr ETBP (Wang et al., 2020). An improvement attributed to increased chain mobility and better stress transfer across phases.

Furthermore, SEM micrographs showed finer PBAT dispersed domains and a more uniform morphology, confirming enhanced miscibility. Exactly the property that was proving to be difficult in the blend. Wang et al. (2020) argue that these changes arise because ETBP's epoxy functional groups react with PLA end groups. Given this interaction, local crosslinked structures are formed, which stabilize the interface. This insight is further supported by thermal analysis, which revealed shifts in glass transition temperature (Tg) and increased storage modulus. These results indicate improved compatibility at both molecular and bulk scales. The practical

relevance of these findings for medical packaging is extremely relevant. Sterile-barrier systems often require films that balance ductility, toughness, and dimensional stability. Wang et al.'s (2020) work contributes important empirical evidence demonstrating that reactive compatibilization can overcome intrinsic weaknesses in PLA/PBAT blends. Therefore, enabling performance levels comparable to petroleum-based packaging materials. Their study provides a clear pathway for optimizing blend formulations to satisfy the mechanical, processing, and durability requirements of sterile medical packaging applications.

Effects of Sterilization Processes on Material Integrity and Sterile Barrier Performance

Krug, Zarges, and Heim (2023) conducted a systematic experimental investigation into how ethylene oxide (EtO) sterilization and gamma irradiation influence the chemical, mechanical, and thermal properties of poly-L-lactic acid (PLLA). Extremely important and relevant research for medical packaging. Given that it will most certainly undergo either EtO or gamma irradiation. Moreover, it is directly relevant because sterilization alters chain structure, crystallinity, and mechanical integrity. Krug et al. (2023) assessed molecular weight, crystallinity, viscosity, tensile properties, color changes, and surface energy to document the extent and mechanisms of degradation for each sterilization method. They found that EtO sterilization induced moderate hydrolytic cleavage, slight crystallinity increases, and reduced elongation at break, but overall maintained bulk structural integrity. On the other hand, gamma irradiation caused significant chain scission, substantial molecular-weight loss, increased brittleness, and discoloration. All of these effects on properties are intensified at higher doses.

Krug et al. (2023) explain that EtO reacts as a gas-phase sterilant producing moisture-driven hydrolysis, whereas gamma irradiation generates free radicals capable of chain scission, oxidation, and crosslinking. All of these findings are relevant to the chemical level of the materials and their overall performance. More specifically, their data showed that irradiated PLLA samples exhibited a sharp drop in elongation at break and tensile toughness, demonstrating that irradiation compromises ductility more severely. Other factors can induce changes and affect properties. For example, the authors state that environmental factors such as humidity and polymer morphology influence the severity of EtO-induced changes. From a sterile-barrier perspective, Krug et al.'s findings have important implications. Increased crystallinity can lead to increased stiffness but decreased toughness, risking crack propagation under package flexing. This is extremely damaging for their candidacy for medical packaging, given that the smallest crack can compromise the sterilization. Overall, Krug et al. (2023) provide a detailed comparison demonstrating that sterilization is not only a microbial-control step but a material-modifying process that has to be considered in packaging design.

To continue on the trend of studies on material performance, Vasile et al. (2022) evaluated how gamma irradiation affects PLA-based blends containing rosemary ethanolic extract and chitosan. These are bioadditives selected for their antioxidant and antimicrobial activity. The authors conducted a multi-stage experimental analysis involving irradiation at 10, 20, and 30 kGy and subsequent characterization of morphology, thermal transitions, crystallinity, antioxidant capacity, and mechanical performance. Their results demonstrate once again that gamma irradiation induces dose-dependent changes in PLA-based blends. Some of these changes include modifications in crystallinity and thermal stability. Interestingly, Vasile et al. (2022)

reported that rosemary extract and chitosan helped mitigate radiation-induced degradation by acting as radical scavengers. This also helps to reduce the rate of chain scission.

The study found that gamma irradiation generally increased crystallinity in the blends due to chain scission, generating new nucleation sites. However, the presence of additives modulated this effect. More specifically, rosemary extract tended to reduce excessive crystallinity growth and maintain more stable thermal behavior. A notable aspect of Vasile et al.'s (2022) work is the evaluation of functional properties relevant to packaging. Gamma-irradiated samples with rosemary extract showed enhanced antimicrobial activity, suggesting a dual benefit: partial protection against degradation and improved antimicrobial performance after sterilization. SEM micrographs revealed that irradiation increased surface roughness and micro-cracking in additive-free materials. However, it also revealed that it had less severe effects in stabilized formulations. These combined efforts are particularly relevant for sterile-barrier packaging that must maintain integrity while providing additional protection against microbial contamination. Without these modifications, gamma irradiation may produce excessive embrittlement and loss of mechanical performance. Vasile et al. (2022) provide compelling evidence that additive engineering is a viable method for improving the sterilization compatibility of PLA-based packaging. The authors also provide a good guideline to follow for future studies on similar matters.

Neffe et al. (2021) studied the effects of ethylene oxide (EtO) sterilization on electrospun PLLA/PDLA core–shell nanofibers. This is a material system relevant to advanced medical packaging and biomedical devices where fiber morphology influences barrier and mechanical

performance. Their work examined changes in molecular weight, crystallinity, morphology, thermal properties, and mechanical behavior after EtO exposure. An important factor to consider about their study is that they used a common and regular EtO cycle: 6 vol%, 45 °C, and 75% relative humidity. The authors found that EtO sterilization produced only minor alterations in nanofiber morphology, with SEM revealing that fiber continuity and diameter distribution remained largely unchanged. Mechanical testing showed slight increases in Young's modulus and corresponding decreases in elongation at break. Neffe et al. (2021) interpret these changes as evidence of limited hydrolytic cleavage, which increases chain packing efficiency without significantly disrupting structure. These are all chemical properties that will heavily influence the overall performance of the material after sterilization exposure.

The authors propose that the high surface-area-to-volume ratio and rapid diffusion of EtO residues in nanofibers reduce hydrolytic stress and limit long-term degradation. Additionally, WAXS analysis showed no major changes in crystallinity. This suggests that processing conditions preserve microstructural stability even under moist sterilization environments. Neffe et al. (2021) underscore that the absence of detectable EtO residues after degassing is critical for material safety. In the context of sterile-barrier packaging, their findings suggest that EtO is compatible with delicate PLA-based microstructures. Overall, the work by Neffe et al. (2021) demonstrates that EtO sterilization can be applied to PLA-based nanofiber packaging or device-protective layers with minimal detrimental effects. Their results contrast with the severe degradation documented under gamma irradiation. All of the conclusions together suggest once again that the decision to select a certain sterilization process must be taken with the morphology of the packaging material in mind.

Conclusion

These bodies of work collectively demonstrate that formulation strategies strongly affect pre-sterilization performance, while sterilization conditions can cause hydrolytic cleavage, chain scission, crystallinity changes, and mechanical losses. However, the existing research has not evaluated how a specific PLA/PBAT medical-packaging format performs after EtO sterilization when compared directly to an established industry standard such as Tyvek. Although researchers have examined material-level changes in films or fibers, and others studied sterilization effects on PLA-based structures, no published studies have combined these domains to assess whether PLA/PBAT pouches can maintain mechanical strength, barrier properties, and microbial integrity in a clinically relevant sterilization process. This missing intersection underscores the need for an empirical comparison that evaluates whether a 32:68 PLA/PBAT pouch can meet or approach the functional benchmarks required of sterile-barrier systems in real medical-packaging use.

Research Question

How does a 32:68 PLA/PBAT biopolymer blend, formed into sealed corner pouches, compare to Tyvek in mechanical properties, and microbial/sterilization compatibility after exposure to standard ethylene oxide (EtO) sterilization?

Methods and Data Analysis

This study proposes using a two-group post-test experimental design to address the research question by comparing the performance of 32:68 PLA/PBAT sealed corner pouches to Tyvek pouches before and after ethylene oxide (EtO) sterilization. The independent variable is

the pouch material (PLA/PBAT vs. Tyvek), and the dependent variables include tensile strength, elongation at break, seal strength, water vapor transmission rate (WVTR), oxygen permeability, and microbial sterilization compatibility. All samples will undergo a standard EtO sterilization cycle, after which mechanical properties will be measured using a universal testing machine, barrier properties will be analyzed using WVTR and oxygen permeability instrumentation, and microbial compatibility will be assessed using biological indicators and post-sterilization sterility verification. All of the same tests will also be performed on samples before sterilization, to later compare and determine if the properties are changed or unchanged.

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3. ISO 2846 LAB REPORT

ISO-2846 Lab Report for Print Production Course
In the undergraduate Print Production course, students collect data required for ISO-2846 testing and are required to create a lab report showing their data and work.

An example follows.

ISO 2846

In this paper we will be talking about the magenta ink comparing to the ISO 2846 Standards

[redacted]

April 23, 2018

Abstract
In this paper we are going to be talking about two different samples of the Magenta Ink, according to the ISO 2846 Standards. I discussed the Delta LAB values, and compared it to the ISO 2846 Standards. We figured out that Magenta 2 fits better with the ISO 2846 Standards than Magenta 1.

Introduction

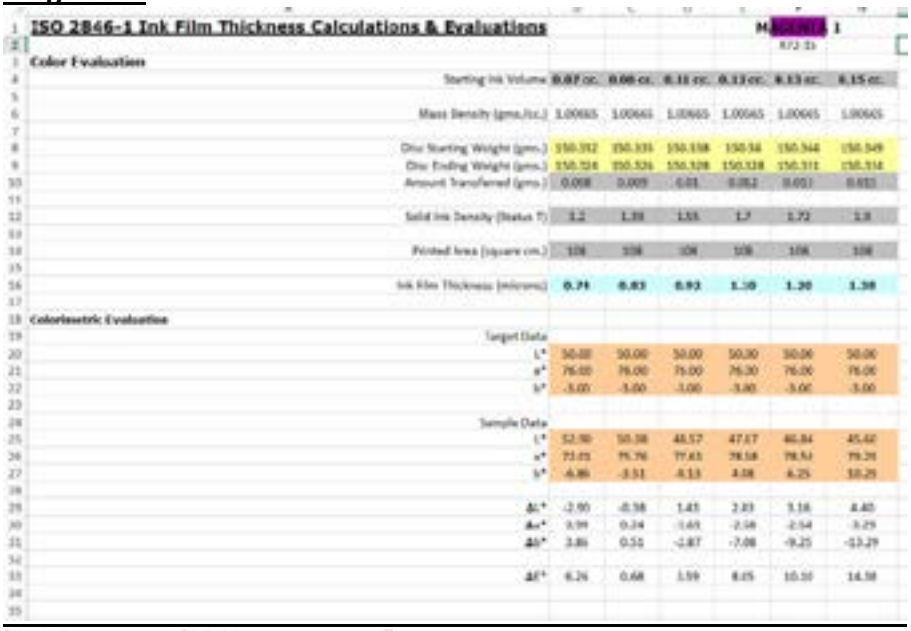
This project is to test out the Magenta Ink to see of it is to the ISO 2846 standards. A lot of ink companies say that their ink is up to the ISO 2846 standards. ISO 2846 "specifies a set of colours which will be produced by a series of inks." It is intended for four-color offset lithography, "when printed under specified conditions, on a defined substrate, using a laboratory printability tester". It provides testing to ensure conformance.

Materials and Methods

ISO 2846 standards allow people to go straight to the numbers because everything will be effected from your opinion of the color. To start to measure it you need to put in a pipet and you want 3CC in it. The difficulty with this is putting the ink in without any air bubbles. Then you measure it correctly, then you need to zero the pipet out and then but the ink in the pipet onto glass and then measure it. You need to get six points therefore, you will have room for range. Then you spread your ink through the roller and so its spread easily and thoroughly throughout the roller. One thing to keep in mind is that the LAB Special paper for testing is very hard to get, there is only one provider. The materials you need is the ink, the roller and the special LAB paper.

Results

Magenta 1



ISO 2846-1 Ink Film Thickness Calculations & Evaluations

Magenta 1

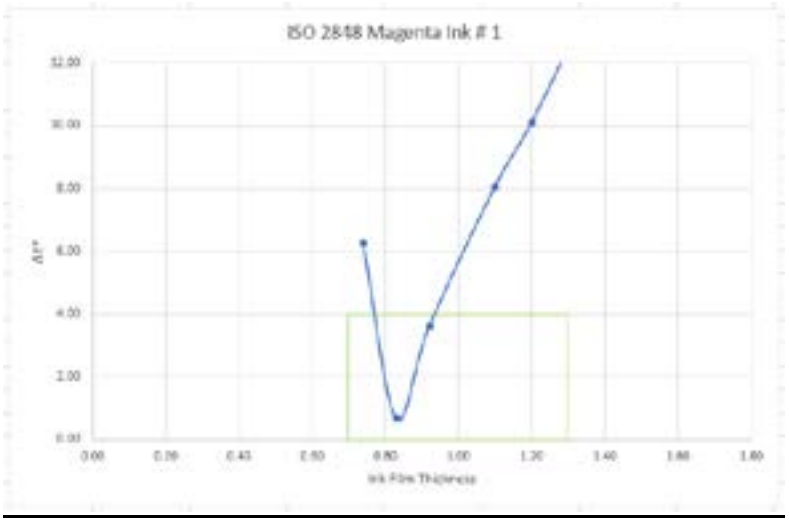
Color Evaluation

	0.07 cc.	0.08 cc.	0.11 cc.	0.13 cc.	0.13 cc.	0.15 cc.
Starting Ink Volume						
Mass Density (gms./cc.)	1.00665	1.00665	1.00665	1.00665	1.00665	1.00665
Disc Starting Weight (gms.)	150.392	150.335	150.338	150.34	150.344	150.349
Disc Ending Weight (gms.)	150.324	150.326	150.328	150.328	150.331	150.334
Amount Transferred (gms.)	0.068	0.009	0.01	0.012	0.013	0.015
Solid Ink Density (Status T)	1.2	1.33	1.55	1.7	1.72	1.8
Printed Area (square cm.)	108	108	108	108	108	108
Ink Film Thickness (microns)	0.74	0.83	0.92	1.10	1.20	1.38

Colorimetric Evaluation

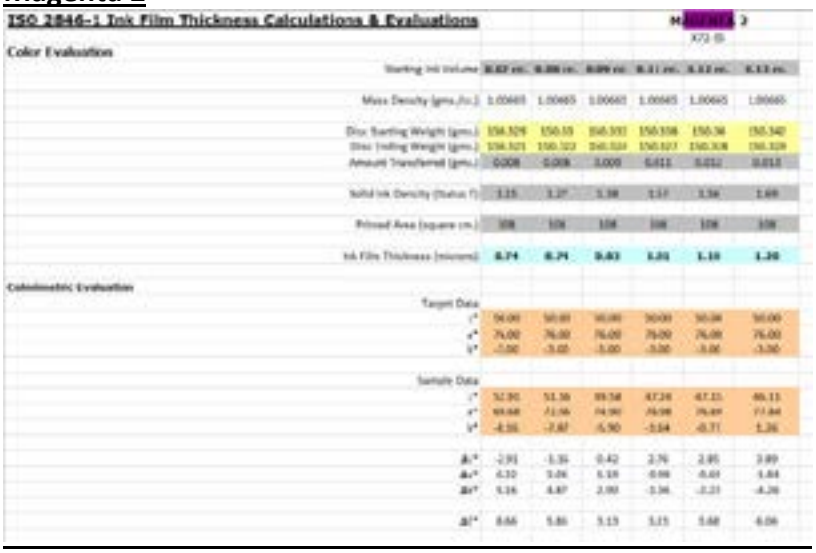
Target Data						
L*	50.00	50.00	50.00	50.00	50.00	50.00
a*	76.00	76.00	76.00	76.00	76.00	76.00
b*	-3.00	-3.00	-3.00	-3.00	-3.00	-3.00
Sample Data						
L*	52.90	50.38	48.57	47.17	46.84	45.42
a*	73.01	75.76	77.43	78.58	78.51	79.29
b*	-6.86	-3.51	-0.13	4.08	6.25	10.29
ΔL*	-2.90	-0.38	1.43	2.83	3.16	4.40
Δa*	3.99	0.24	-1.43	-2.58	-2.54	-3.29
Δb*	3.86	0.51	-2.87	-7.08	-9.25	-13.29
ΔE*	6.26	0.68	3.59	8.05	10.10	14.38

IFT	ΔE*
0.74	6.26
0.83	0.68
0.92	3.59
1.10	8.05
1.20	10.10
1.38	14.38



In the light green box is the ISO 2846 standards and at the film thickness this Magenta ink will be correct for ISO 2846 standards. Here there is only two spots where they fit the ISO 2846 Standards.

Magenta 2

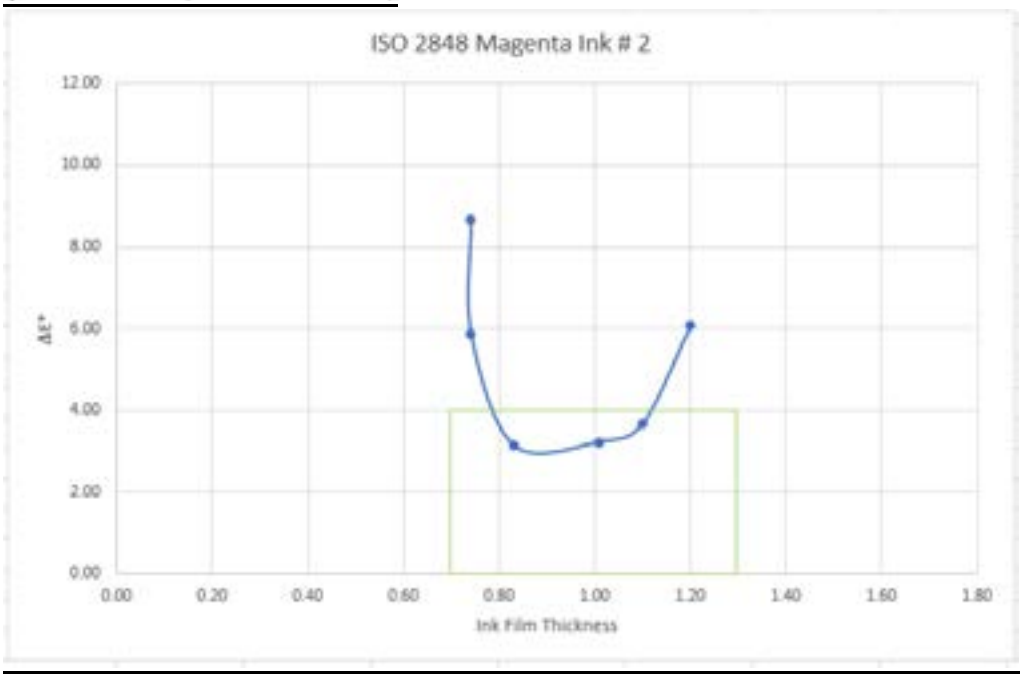


ISO 2846-1 Ink Film Thickness Calculations & Evaluations

Color Evaluation

Colorimetric Evaluation

IFT	ΔE*
0.74	8.66
0.74	5.86
0.83	3.13
1.01	3.23
1.10	3.68
1.20	6.06



In the light green box is the ISO 2846 standards and at the film thickness this Magenta ink will be correct for ISO 2846 standards. Here there is three spots where they fit the ISO 2846 Standards. Therefore this Magenta Ink is better for the ISO 2846 Standards.

Discussion and conclusions

As you can gather the Magenta 2 is better for the ISO 2846 Standards because more of the points are in the range. Because it was on the same paper and under the same circumstances Magenta 2 is better and fits in the ISO 2846 Standards. Magenta 1 is only good for two points in the ink filminess. Future experiments, will include the ink filminess and a change in Delta LAB.

Citations:

ISO 2846-1 PowerPoint by Bruce Myers.

4. T A G A T - S H I R T

For the 2025 Technical Association of the Graphic Arts (TAGA) conference in Boulder, CO, students designed, tie-dyed, and printed T-shirts for the student competition. The resulting shirt incorporated imagery from Colorado and the City of Boulder, along with the RIT Tiger. The resulting shirt was selected by the judges as the winner in this category.

The design highlighted the state of Colorado and the City of Boulder through imagery and color selection, and used a western-style typography motif.

The white shirts were tie-dyed in the red, yellow, and blue of the Colorado State Flag

Students prepared, exposed and washed the screens

Black, Red, and Yellow plastisol screen printing inks were mixed and used for the carefully registered three color printing

At the TAGA conference, the students proudly displayed their work, in this case, the t-shirt and a package design

During the TAGA conference awards banquet, the RIT students were recognized for winning both the t-shirt and packaging design categories

5. BOOK PRODUCTION

In the Lithographic Production course in 2018, students produced a book "Test Targets 11" as part of the the course requirements. The resulting book is comprised of student and faculty research, and students did all the premedia work, including proofing. The book was printed at a local commercial printer with the students in attendance, and bound at a local bindery, again with the students in attendance. This project was in addition to hands-on work in the materials laboratory where students evaluated substrates, inks, and fountain solution, as well as paper feeding, transport, delivery, and ink key adjustments using a small lithographic press on campus.
Samples at each stage of production were saved, and used to describe important printing concepts, including imposition and binding.

The resulting book was completed by the end of the semester so that students could take them home with them. They were also mailed to alumni and industry partners.

Students observed the press run at a high volume printer

Students observed the press run at a high volume printer, including platemaking, mounting, and performing the press ok

In a trip to the bindery, students observed the books being bound and learned about the technology and equipment involved

Samples were saved at each stage of the production to use as a sample to discuss print production in subsequent courses

6. KODAK TRADE DRESS

Students in the undergraduate capstone Team Project course work together on a project demonstrating key learning outcomes from the program. Typically, this project is together with an industry partner. In 2018, the professor of the course was struggling with an appropriate topic. As the Department Chair at that time, I contacted the marketing management at Eastman Kodak company and discovered that they were looking to replace their trade dress collateral, essentially carefully produced color cards that are distributed to printers reproducing the Kodak Red and Yellow. The students met with Kodak marketing for the project parameters and worked with the Printing Applications Lab at RIT to produce the trade dress cards on an HP Indigo Press. The colorimetric parameters for the job were very strict, and students needed to apply their skills from the color management course in addition to printing production workflow, project management, and page composition techniques. The resulting cards were enthusiastically accepted by Kodak, and the students gained valuable insight into printing production.

Students outside of Kodak's Rochester, NY headquarters after meeting with marketing managment about the trade dress requirements

The printed cards required several iterations of adjustments to meet ther strict colorimetric requirements for the unique job


The final trade dress cards were printed 2-up on an HP Indigo Press with custom inks. Students oversaw all aspects of print production

Kodak Marketing Director signing off on an approved card at a press ok

Students conduct a formal presentation to faculty, fellow students, and Kodak marketing personnel

7. TRIP TO ITALY - 2025

The Italian Technology Award for the Graphic, Printing, and Converting Industries (ACIMGA) through the Italian Trade Agency, Chicago, IL approached RIT about a student paper writing contest which entailed students writing papers to win a trip to Italy. The opportunity was available to 3rd and 4th year BS students and MS in the packaging and printing programs. Over the course of six weeks, I met with interested students to help with their writing and research, four students were selected to go on the trip in June, 2025. Students could choose from one of the following topics:

1. Explain the relationship between printing technologies and de-inking from a sustainability and recyclability point of view. What is the impact of different inks on different printed materials?
2. Lamination and multi-laminated materials in flexible packaging: where is the legislation at? What are the regulatory differences in the different countries across the world? What are the common aspects?

The charge was to write a 10,000 characters = 1,600 words or 3.5 pages single-spaced.

Submitted Paper Titles are as follows:

- Unpacking Multi-Layered Materials: Germany, Italy, India, and the US's Regulatory Approaches to Flexible Packaging Waste
- Global Extended Producer Responsibility Policies
- Design and Plasma De-Inking: Advancing Sustainable Recycling
- Comparing Conventional Mechanical Flotation and Enzymatic De-inking in Recycling of Offset-Printed Publications

The four resulting papers follow.

Unpacking Multi-Layered Materials: Germany, Italy, India, and the US's Regulatory Approaches to Flexible Packaging Waste

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4/25/2025

Flexible packaging, often made of multiple materials laminated together, has become essential for modern packaging, offering a wide range of properties for food, pharmaceutical, and consumer goods. These same qualities make recycling laminated packaging notoriously difficult, presenting challenges for sustainability goals worldwide. Regulatory approaches to laminated packaging vary significantly, with the EU promoting designing for recycling incentives with Extended Producer Responsibility (EPR) laws, India directly legislating multi-layered plastics, and the US relying on state laws and corporate initiatives. Centralized regulation, economic incentives, and cultural waste management practices shape the recyclability of laminated packaging worldwide.

Laminated packaging typically combines different materials like paper, polymers, and aluminum to deliver specific properties that a single material could not achieve. These layers are bonded together through a lamination process to form a structure that is lightweight, durable, and often resistant to moisture, oxygen, and light. Common examples are single serve items for snack packages, pharmaceutical packaging, and metalized films. Each layer has its own purpose, providing strength, sealing, barrier properties, and printing capabilities. After use, separating these materials for recycling is technically and economically challenging. As a result, these materials are often excluded from traditional recycling streams and are sent to landfill or incinerated.

In the European Union, the Packaging and Packaging Waste Directive and Single-Use Plastics Directive establish ground rules for members to regulate packaging materials, including laminated materials. These directives support EPR laws which dictate that producers bear fiscal responsibility for waste generated. Germany and Italy, both members of the EU, have adopted diverse ways to enforce these measures. India is the only country to explicitly have regulations for laminated plastic packaging and its informal sector plays an especially key role in implementing these regulations. The U.S. on the other hand, lacks any federal policy for flexible packaging, instead leaving it to the states to make the decisions.

Germany stands out for its approach to regulating multi-layered materials through a structured EPR system. Under its VerpackG Packaging Act, packaging is categorized based on its ability to be recycled and producers are charged fees accordingly. Packaging that does not fulfil the requirement of eco-modulation is taxed at a higher rate than environmentally friendly packaging (Packaging Europe, n.d.). Non-recyclable materials, like laminate structures that are not recyclable with current infrastructure, are penalized thus incentivizing the use of sustainable, recycled materials. Germany's advanced infrastructure, including material recovery facilities, enhance the country's capacity to process laminated materials. Even with this infrastructure, these materials still pose technical and economic challenges. Germany's focus on producer accountability, recyclability criteria, and research makes them a leader in management of laminated packaging waste. Recent developments include the introduction of a Single-Use Plastics levy in 2024 targeting producers or certain plastic packaging materials with payments expected to start in 2025, reinforcing the fiscal responsibility of producers (Ernst & Young n.d.).

Another country in the EU stands out for its approach on EPR laws and regulating laminated materials. Italy's EPR system is coordinated by a private non-profit consortium, CONAI, which ensures

packaging producers achieve their recycling and recovery targets of packaging waste that is set by law. CONAI's recent adjustments have further penalized non-recyclable materials. Although Italy lacks specific legislation targeting laminated plastic, its system differentiates among packaging materials based on recyclability, with higher fees for laminated plastic. Fees for plastic, aluminum, and paper packaging have increased, and there have been reductions in the fee structure for compostable and easily recyclable materials (CONAI, 2024). In response to EU circular economy goals, Italy has launched projects focusing on innovative recycling methods and compostable multi-layered materials. Although there is a regulatory gap in directly naming multi-layered materials or laminated plastic, the financial disincentives serve in its place. Regional enforcement differences in infrastructure remain a concern, especially in southern areas, but the centralized fee structure provides uniform incentives across the country.

India is also prominent when it comes to regulations on laminated materials. India is the only country that explicitly legislates the recycling of multi-layered materials. The Plastic Waste Management Rules, most recently updated in 2024, specifically addresses laminated materials by requiring producers to either recycle or recover energy from these materials. The rules prohibit non-recyclable or non-energy-recoverable materials making it one of the few nations to restrict such packaging (Government of India, Ministry of Environment, Forest, and Climate Change, 2022). The legislation mandates collection and recycling targets under an EPR framework, overseen by the Central Pollution Control Board (CPCB). India's inclusion of laminated materials in legal definitions ensures clarity and compels producers to think about their packaging design.

India's informal recycling structure also plays a significant role in the implementation and enacting these policies. Informal collectors collect waste to then be separated and processed for selling, reuse and downcycling. Laminated materials often have a lower resale value which decreases the incentive to collect the material. While this sector operates outside of the formal government and economy, it is vital to the material recovery chain. Various non-governmental organizations are working towards integrating informal workers into formal systems by offering incentives like training, protective gear, and recognition. However, variations in implementation persist across different states. Urban areas like Pune have developed efficient laminated material collection systems while rural regions often face a lack of infrastructure. Enforcement is another key issue as many producers fail to comply with mandated targets due to limited monitoring. As of late, India has mandated barcodes or QR codes to be placed on all plastic and laminated packaging by July 2025 to improve traceability, exempting micro, small, and medium enterprises from EPR obligations to reduce the burden on small businesses (Packaging Gateway, 2023).

In contrast to India, the United States lacks a federal policy that specifically regulates flexible packaging. Instead, regulation is up to the states, with states like California and Oregon pioneering legislation inspired by EPR laws. California's SB 54 mandates that all single-use packaging must be recyclable or compostable by 2032, and it requires organizations that produce these materials to take responsibility for managing packaging waste, including laminated materials (California Legislature, 2022). Oregon's SB 582 similarly introduces a shared responsibility system for packaging waste; however, it does not directly call out multilayered or laminated materials (Oregon Department of Environmental Quality, 2023). These laws represent noteworthy progress, however, since they are at the state level, material regulation varies widely across the country.

Nationally, a great deal of the effort to address recycling laminated packaging comes from voluntary commitments. Industry groups like the Flexible Packaging Association (FPA) and U.S. Plastics Pact promotes designing for recyclability guidelines and investing in advanced recycling technologies. Still laminated materials remain one of the most challenging categories to recycle due to their incompatibility with current mechanical recycling infrastructure. Chemical recycling methods, like depolymerization and pyrolysis, are being piloted to address this issue, though questions about scalability and environmental impact remain. The absence of centralized federal regulations limits market development for recyclable laminates and creates consumer confusion about proper disposal. Recently, New Jersey proposed legislation that would require all packaging to be recyclable or compostable by 2034, signaling a trend toward broader regulatory coverage (Associated Press, 2023).

Despite the differences, several commonalities exist. Across all regions, EPR is emerging as a central tool to shift responsibility to producers. Additionally, eco-modulation fees based on material recyclability are gaining traction. Technical challenges in laminated material recycling remain universally difficult, and innovation in material design and separation technologies is a shared priority (OECD, 2023). Research into mono-material alternatives and solvent-based separation techniques continues to grow, with both government and private sector support. Public awareness campaigns and labeling initiatives, such as the EU's harmonized recyclability labeling or the How2Recycle label in the U.S., aim to improve sorting behavior and recycling outcomes.

Cultural and economic factors influence the implementation of these regulations. For example, Germany's strong environmental governance contrasts with India's informal recovery system, while the U.S. continues to rely on market-based solutions and state legislation. Public willingness to pay eco-modulated fees or participate in source separation programs varies widely. In countries with a culture of environmental responsibility, such as Germany, there is higher compliance and innovation in sustainable packaging. In India, economic necessity drives high levels of material recovery through informal labor. The U.S. remains caught between consumer expectations and industry interests, though recent state-level momentum shows a potential shift toward stronger policies.

The recyclability of laminated packaging is shaped by a complex dynamic of regulation, economic structures, and local waste management culture. While countries like India lead in explicit legislation of multi-layered plastics, the EU's structured EPR systems and the U.S. 's industry-driven strategies demonstrate varied pathways toward managing these materials. Recycling capability infrastructure is a noteworthy factor, as evidenced by its critical role in the relatively advanced systems in place in Germany. To improve the sustainability of flexible packaging, it is essential for policymakers to align incentives, strengthen enforcement, and promote innovation in recyclable design. Dialogue between government and industry stakeholders, including printers, converters, and consumer brand companies are required to advance these initiatives. Increased global coordination can inform benchmarking and best practices, and investment in alternatives to existing laminate technologies developed for enhanced recyclability will be essential to closing the loop on flexible packaging, particularly as demand for convenience and shelf-life protection continues to grow.

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Global Extended Producer Responsibility Policies

Laminated and multilayer laminated film is used to produce packages all over the world. While these films are very useful in protecting and packaging products, the use of these materials creates a question – what do we do with these films when their intended purpose is over? Waste, and more specifically packaging waste, is a major global problem with 40% of the world's plastic waste coming from packaging (Samborska). In response, countries around the world have looked to implementing extended producer responsibility (EPR) policies as a solution to this waste problem. For example, Canada, the United States of America, India, and Brazil have all sought out ways to implement such policies. While similarities exist between EPR policies in each of these countries, there are also notable differences in the methods used by governments to address plastic packaging waste via extended producer responsibilities for laminated and multilayer laminate packaging films.

EPR policies can be executed in different ways, however, each method has the same goal – to make "producers responsible for their products along the entire lifecycle" ("Extended Producer Responsibility" p.6). The idea is simple, if producers are responsible for taking care of the waste that their products make, they will have more incentive to reduce the amount of waste they produce from their products. This system also puts less strain on governments as they will not have to dedicate funding and resources to waste management initiatives.

EPR policies are generally implemented in two ways – financial or operational. In financial EPR policies, the government is still responsible for the country's waste management systems, however, producers must pay a fee, the net cost of which usually aims to cover all the expenses to collect and dispose or treat waste ("Extended Producer Responsibility"). In operational EPR policies, producers are held accountable for creating a waste collection and recovery system and fund the operational costs of the system ("Extended Producer Responsibility"). It is common for policies to include an optional or required use of a producer responsibility organization: a group of producers who join together to meet the requirements of the EPR policy ("Extended Producer Responsibility"). The specifics of the policies implemented in each country vary to meet the needs of that country, but in general, each policy is similar in its goals and core requirements.

In Canada, EPR policies are implemented not by the federal government, but by the provincial government. These policies have been put into effect in the majority of the Canadian provinces. Some of the provinces that do have EPR policies include Ontario, British Columbia, and Manitoba ("EPR in Canada: Circular Materials"). As the policies are decentralized by the federal government to the province level, the requirements and scope differ. This allows provinces to implement policy specifics that are best for them but may not work as well or be agreed to as much in other provinces. For example, Ontario's Blue Box law focuses on the collection of recyclable materials as its namesake, Ontario's blue recycling boxes, suggests. This law, which was established in 2016 with its most recent amendment added in 2024, focuses on

an operational approach with every producer required to establish and operate a collection system ("O. Reg. 391/21: BLUE BOX"). Under this law, producers must recover 25% of their flexible plastic waste annually between 2026-2029 and 40% annually from 2030 and onward ("O. Reg. 391/21: BLUE BOX"). British Columbia has adopted a similar, and more strict, operational EPR policy. Under British Columbia's law that was established in 2004 and last amended in 2025, producers must provide consumers with free access to collection facilities and must reach a 75% recovery rate of all packaging waste they produce ("Environmental Management Act: Recycling Regulation"). In contrast to Ontario and British Columbia, Manitoba utilizes a financial EPR policy. Manitoba's law created in 2008 and last amended in 2014, requires producers to pay a fee, the total of which will fund up to 80% of Multi-Material Stewardship Manitoba, the province's residential packaging and printed paper recycling program ("Manitoba: Circular Materials"). Clearly, the policies between provinces can vary greatly. From an operational to a financial focus and the requirements that producers must meet, provincial policy differences can cause confusion for companies spread across multiple provinces but allows the provincial government to implement regulations that are deemed most effective for them.

Like Canada, the United States also does not have federal EPR policies, however, unlike Canada, the majority of states do not have these policies in place. To date, only 12 states have introduced legislation for an EPR policy, only five of these have been passed by state governments ("Introduction to the Guide for EPR Proposals"). In 2022, California passed Senate Bill 54, which targets all producers of plastic packaging, including multilayer flexible packaging. These producers are required to join a producer responsibility organization to reach a 30% recycling rate by 2028 and a 65% recycling rate by 2032, unless the individual producer can demonstrate proper compliance alone ("California State Senate Bill 54 Chaptered 2022"). In February of 2025, New York introduced, but has not yet passed, Senate Bill 5062 to require producers of packaging waste to join a producer responsibility organization. This bill does not have specific recycling rate targets, instead producer responsibility organizations must perform a needs assessment and have an approved plan with recycling targets based on the assessment ("New York Senate Bill 5062 (Introduced)"). Without specific targets, producers are given more flexibility to create meetable targets based on the needs of the state, however, these targets will likely be less rigorous than targets implemented directly into the policy. When the federal government does not implement EPR policies, many states will likely de-prioritize the implementation of their own policies.

Outside of North America, federal EPR policies are more common. In India, an EPR policy was established under the Plastic Waste Management Rules of 2016, which was most recently amended in 2024. Unlike many policies that generally target packaging of all different materials, this policy specifically focuses on plastic packaging. This allows for the policy to categorize and set individual goals for different types of plastic packaging, category II being single and multilayer flexible packaging ("Categories of Plastic Packaging Under EP"). This policy is more operationally focused with producers having to ensure certain recycling goals are met while taking steps to minimize the amount of plastic waste generated. Producers of category II plastic packaging must reach a recycling rate of 30% from 2024-2025, which increases yearly

to 70% for 2027-2028 and onwards ("Plastic Waste Management Amendment Rules 2024"). Having a centralized policy allows producers across the country to have to follow the same guidelines, resulting in less confusion of what goals to meet and a system in place to deal with plastic waste across the entire country.

While many EPR policies are similar by setting goals and allowing producer responsibility organizations to be formed, Brazil takes a unique approach. In 2023, Brazil implemented a policy that established the use of three different certifications that producers of packaging waste can obtain. Producers must choose one of the three certifications in order to meet reverse logistics requirements (de Paula Patulski et al.). The first certification is the Reverse Logistics Recycling Credit Certificate (CCRLR) that producers can receive by keeping track of how much of their waste is collected and providing proof of giving compensation to already established waste sorting and recycling services for collecting, sorting, and recovering the producer's waste (de Paula Patulski et al.). This shifts the financial burden of waste collection from the collectors and onto the producers. The next certification is the General Packaging Structuring and Recycling Certificate (CERE) in which producers may make financial investments to waste collection, sorting, and recycling systems proportional to the amount of packaging they would be required to recover (de Paula Patulski et al.). This provides producers the opportunity to not actively track their waste, while building infrastructure and improving the capacity and capability of waste and recycling streams. The last certification is the Future Mass Credit Certificate. This certificate allows producers to exceed their reverse logistics requirements and hold the extra as credit to be used in the future (de Paula Patulski et al.). This allows producers to not have to worry as much about recovering their waste in the future and allows for better financial planning. Brazil's EPR policy is very unique. While other policies treat each producer the same, giving them the same goals, Brazil gives producers different options for them to choose what is best for them while still building and funding the recycling system.

As many of these policies are new, their effectiveness is difficult to gauge, however, many older policies have been proven to be effective. EPR policies have been shown to improve recycling access and participation, improve and optimize recycling infrastructure, and provide better education on recycling ("Increasing Recycling Rates with EPR Policy"). In British Columbia, the total packaging recycling rate has increased from 50-57% in 2012 to 81% in 2021 and increased plastic recovery from 41% to 55%, with much of the flexible plastic being converted to fuel or more properly disposed of ("Increasing Recycling Rates with EPR Policy"). In South Korea, the plastic container and film recovery rate increased from 68% in 2003 to 91% in 2019 ("Increasing Recycling Rates with EPR Policy"). Belgium's plastic recycling rate increased from 37.6% in 2012 to 52% in 2021 ("Increasing Recycling Rates with EPR Policy"). These recycling and recovery rate increases show that EPR policies can be a successful method to improve waste management, especially for flexible plastic packaging.

EPR policies vary around the world. Whether these policies are implemented federally or at a state or provincial level or have a financial or operational focus, they put a system in place to address waste. Recognizing that laminated and multilayer laminated plastic packaging is a large contributor to waste throughout the world and presents unique challenges for recycling, EPR work is clearly needed. EPR policies that facilitate a dialogue between government and industry

will likely help build successful recycling systems that will address these challenges. Furthermore, clear guidelines that result in certifications accompanied by educational initiatives could help drive consumer choice and thereby pressure laminate materials manufacturers to take a more active role in the circular economy. Further study on the effectiveness of existing programs could uncover best practices and inform implementation strategies in certification programs and regulatory efforts. The adoption of policies such as these can greatly change how waste is recovered throughout the world.

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Design and Plasma De-Inking: Advancing Sustainable Recycling

In today's environmentally conscious world, paper recycling stands as a cornerstone of sustainable material management. According to Two Sides (N.D.), "paper is one of the most recycled products in the world and promises the circular economy model of make, use, recycle, and reuse." Central to this recycling process is "de-inking[1]"—the critical step of removing printed colorants from paper fibers to enable their reuse in new products.

While traditional printing methods rely on hydrophobic, solvent-based inks that respond well to conventional flotation de-inking techniques, the rapid expansion of digital printing technologies has introduced significant recycling challenges. Inkjet printing, in particular, employs water-soluble dyes and fine pigment particles that resist standard flotation separation methods, threatening to disrupt established recycling streams and undermine sustainability goals.

This growing incompatibility between modern printing technologies and recycling methods has spurred innovation in de-inking approaches. Among the most promising advancements is plasma de-inking—a process that harnesses ionized gas to modify ink components at the molecular level. This emerging technology offers a potential solution for the previously intractable problem of removing digital printing inks, helping to maintain paper's position in the circular economy despite evolving printing technologies.

Differing ink and paper formats greatly influence the efficacy of recycling due to their unique chemical properties and interactions. For example, Fischer et al. (2022) reported that roughly 81% of offset/gravure prints (newspapers, magazines) pass standard de-inkability flotation tests, while most inkjet prints fail due to poor luminosity and heavy "dirt" loading. Likewise, waterless offset printing and dry toner (polymer toners fused by heat) tend to de-ink well, but liquid toners or UV-cured coatings often produce stubborn films. Inks with high pigment concentration on thin paper (e.g., tabloid flyers) can also lower brightness after recycling, further hindering de-inking.

The key to designing optimal de-inking strategies starts from the ink chemistry (water- or solvent-based, dye vs. pigment vs. polymer), print method (e.g., offset, flexo, inkjet), substrate (uncoated paper, coated paper, plastic film), and coating formulation (e.g., use of primers, coatings, varnishes). For instance, multilayer plastic packaging often uses adhesives and inks that are created to ‘stick,’ protecting product quality; this makes recycling difficult unless special coatings or separation layers are used. Designing print products with de-inkability in mind is crucial. As the Nordic Swan Ecolabel (2020) notes, “de-inking on an industrial scale is highly complex” and requires inks and coatings that do not hinder fiber

[1] De-Inking: the process of removing ink from wastepaper to prepare it for recycling into new paper products. It involves separating ink particles from the paper fibers, typically using a combination of mechanical and chemical methods, including flotation. It encapsulates all forms of ink (UV, dye, pigment, latex inks, etc.

recovery. Thus, printing choices from the outset—ink selection, process parameters, and substrate type—set the stage for how well inks can be removed later.

These challenges are being addressed with plasma-based de-inking technologies. Plasma de-inking uses ionized gas or "cold plasma" to oxidize or fragment ink components without wet chemicals. In atmospheric pressure systems, gases such as air, He, N_2, or O_2 are ionized to produce reactive oxygen and nitrogen species (RONS). This is the same method used to improve ink adhesion via Corona treatment to plastic substrates. Typically run as a pre-treatment to flotation removal, plasma's greatest strength is "loosening" tough pigment. The RONS attack the ink's matrix, introducing polar and oxidized surface groups on fibers and pigments. In effect, plasma "pre-conditions" the print surface to aid flotation, increasing surface energy that can etch or embrittle the ink film. For example, atmospheric DBD or corona systems generate O, O_3, OH radicals and metastables that diffuse into the paper surface, breaking bonds in dyes/resins and boosting wettability—essentially making the fiber hydrophilic (Mauchauffé et al., 2024).

Plasma methods can be categorized into three main types: corona discharge (high-voltage needle creating micro-discharges), dielectric-barrier discharge (DBD; electrodes separated by a dielectric barrier), and plasma jets (localized jets driven by radiofrequency or microwaves). All operate at or near room temperature (hence "cold plasma") and can treat surfaces in-line. In contrast to other processes, like ozone or chemical bleaching, plasma uses air or inert gas, consumes no water, and produces minimal secondary waste. As Mauchauffé et al. (2024) explain, "open-air atmospheric plasma methods...modify surfaces...without need of solvents and without high running cost vacuum systems, making them eco-friendly and easily scalable."

Mechanically, plasma introduces polar groups (–OH, –COOH) on cellulose fibers and pigment surfaces. This dramatically lowers the water contact angle of paper. A study using corona plasma dropped the contact angle from ~104° (untreated) to ~60° (after 10 minutes), indicating greatly increased wettability. This promotes fiber swelling and helps detach ink particles. Plasma is typically combined with flotation: paper is treated, pulped, and then air-bubbled in water to remove oxidized ink debris. Although not yet commercialized at scale, plasma de-inking shows significant promise. Early trials highlight its environmental advantages—including dry processing, minimal chemical waste, and faster treatment cycles—making it a compelling candidate for future large-scale recycling systems.

Researchers investigating plasma de-inking have reported promising results across various technological approaches. The following case studies highlight three key applications: helium plasma for inkjet prints, corona discharge for multicolor prints, and cold plasma for enhancing paper fiber hydrophilicity.

Inkjet printed paper exhibits particularly promising results with plasma treatment. Mauchauffé et al. (2024) treated inkjet prints with atmospheric helium plasma (open-air DBD) and documented significant improvements. Using spectrophotometry and SEM/FTIR analysis, they found that plasma "speed[s] up the de-inking" process without damaging paper structure. The treatment nearly doubled the de-inking rate in their tests, while SEM and FTIR confirmed that fiber morphology and chemistry remained largely intact. Critically, they observed that plasma increased paper surface hydrophilicity, which "enhance[s] fiber swelling... and lead[s] to faster ink removal" (Mauchauffé et al., 2024). In essence, plasma made the fibers absorb water more readily, promoting pigment wash-out during subsequent flotation processes.

Building on these findings, other researchers have developed a Corona discharge system specifically addressing multicolor inkjet prints, which historically have been exceptionally difficult to de-ink. By using targeted plasma activation on harder-to-remove pigments, they achieved significant partial ink removal: approximately 48.6% de-inking for yellow ink, 64.1% for blue, and 41.1% for red. These figures represent the percentage of ink removed in lab de-inkability tests after plasma pre-treatment.

Importantly, the authors reported minimal impact on paper integrity: tensile strength loss was less than 10% compared to untreated controls. This demonstrates that even short plasma exposure can effectively oxidize stubborn pigment films without severely weakening the substrate. Microscopic analysis further revealed that the ink layer was thinned and fractured by plasma treatment, facilitating its release during washing. Rather than replacing existing methods, plasma serves as a powerful adjunct—enhancing ink removal efficiency when used with flotation or other conventional techniques.

Examining the fundamental mechanisms at work, Gaiolas et al. (2013) applied low-pressure cold plasma to raw paper (without ink) to study fiber swelling effects. Contact-angle and disintegration tests revealed dramatic improvements: plasma-treated sheets broke down in water substantially faster than untreated ones. For equal pulp quality (first-order entropy), the untreated paper required significantly longer mechanical agitation than the plasma-oxidized paper (Gaiolas et al., 2013).

XPS analysis confirmed that plasma treatment introduced oxygen-rich groups on the fiber surface, which directly correlated with easier repulping. In practical terms, the treated samples needed fewer rotation-minutes to reach the same fiber dispersion (Gaiolas et al., 2013). Though not a de-inking test per se, this study supports the fundamental principle that increasing fiber wettability via plasma (as evidenced in the contact-angle data) reduces energy requirements for various recycling steps (Kusano, 2024).

These case studies collectively illustrate several tangible benefits: plasma treatment can markedly increase the hydrophilicity of paper, shorten pulping time, and remove a substantial fraction of inks without requiring solvents. While ink removal is typically partial rather than complete, the collaboration between plasma pre-treatment and conventional flotation holds significant promise. Moreover, the low-temperature nature of nonthermal plasma minimizes thermal damage—treated papers in these experiments retained essentially their original strength and fiber integrity.

Beyond ink chemistry, substrate characteristics significantly impact de-inking effectiveness. Paper fibers' porosity allows interaction with plasma treatment throughout their structure. Priyanti et al. (2021) showed that corona plasma "penetrates the front surface and deep into the back side" of paper, creating comprehensive hydrophilicity changes—a key advantage over surface-only treatments.

Plasma de-inking remains an emerging technology primarily in research stages, with high-throughput commercial systems still under development. Early results reveal compelling advantages: dry operation, elimination of chemical effluents, and reduced processing times compared to conventional methods—all aligning with increasingly stringent environmental regulations.

The interdependence between print design and de-inking technology forms the foundation for sustainable printing materials. Forward-thinking choices in inks and substrates establish optimal conditions for subsequent recycling. Plasma-based approaches complement traditional methods by using reactive gas species to modify inks without harsh chemicals while maintaining fiber integrity.

Still, plasma is not a one-size-fits-all fix. Its performance depends heavily on ink composition and substrate characteristics, often achieving only partial results with heavily coated or UV-cured prints. Like other recycling methods, effective sorting remains essential.

Current research shows promising results with 40–60% ink removal rates in laboratory settings. Advancing this technology requires developing higher-throughput systems and hybrid processes combining plasma with enzymatic or alkaline washing.

For industry stakeholders, the key insight is straightforward: by aligning printing practices with plasma treatment capabilities, manufacturers can substantially enhance recyclability, moving closer to truly sustainable circular material flows

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Comparing Conventional Mechanical Flotation and Enzymatic De-inking in Recycling of Offset-Printed Publications

The global printing and publishing industry continues to rely heavily on offset printing, particularly for newspapers, magazines, and other high-volume publications. As these printed materials circulate in large volumes, they also contribute significantly to the supply of paper available for recycling. In fact, recovered paper especially from newsprint which is a vital raw material within the European paper industry, supporting a circular economy and helping to meet sustainability targets through efficient resource reuse (European Paper Recycling Council, 2017). In order to render printed paper suitable for recycling, de-inking, which entails removing ink particles from the paper fibers, is a crucial step in the recycling process. This industrial technique is crucial because it allows the fibers to be recycled back into papermaking, improving sustainability by reducing the demand for new fibers (Urška & Klemen, 2022). As the demand for sustainable paper recycling increases, efficient de-inking of printed papers becomes even more crucial.

The ability to successfully remove ink not only determines the quality and usability of recycled fibers but also plays a pivotal role in reducing environmental impact and conserving resources. As outlined in recent studies, Houssni et al. (2022) and Singh and Sharma (2020), suggests that such improvements lower environmental impact and promote cleaner recycling processes, further aligning with sustainable manufacturing goals. De-inking is comprised of several steps, including repulping, de-inking agent treatment, flotation, hand sheet making, and evaluation of the produced hand sheets (Yang et al., 2022).

Offset printing, particularly heat-set varieties, poses major challenges for de-inking due to the resin-rich, hydrophobic nature of the inks and their deep penetration into paper fibers. These ink formulations resist fragmentation and water dispersion, making them difficult to detach during conventional flotation, which relies on air bubbles and surfactants to remove ink particles (Monte et al., 2019). The ink's binder forms a strong film on the fiber surface and penetrates the substrate, further reducing flotation efficiency (Nguyen et al., 2017).

Mechanical flotation, though effective for certain ink types, often fails to adequately remove offset inks, leaving behind ink specks and resulting in lower brightness and recyclability. The particles tend to remain too large or hydrophilic, limiting their attachment to air bubbles during flotation (Fang et al., 2022). In response to these challenges, enzymatic de-inking offers a promising solution. Enzymes such as lipases and esterases target ink binders by breaking down ester linkages, while cellulases alter the fiber surface, loosening the ink-fiber bond (Singh & Sharma, 2020). This biochemical action promotes better ink release even before flotation.

The present paper reviews flotation de-inking technology and then discusses the promise of enzymatic de-inking technologies, particularly regarding papers printed with the offset lithographic process. Literature supporting the efficacy of enzymatic processes is then reviewed, with special emphasis on

environmental benefits of this technology, followed by information about the economic impact for practitioners choosing to adopt enzymatic de-inking techniques.

Conventional Mechanical Flotation De-inking

Flotation de-inking is defined by The Paper Industry Technical Association (2016) as a process in which air bubbles selectively attach to hydrophobic ink particles, lifting them from a pulp slurry and allowing them to be skimmed off, thereby separating ink from reusable paper fibers. Conventional flotation de-inking has been the mainstay in paper recycling for decades. The process involves re-pulping printed wastepaper in water, aided by surfactants and mechanical agitation to detach ink particles from fiber surfaces. Air is then injected to form bubbles that carry the hydrophobic ink particles to the surface, creating a froth that can be skimmed off (Monte et al., 2019).

While this method is effective for many ink types, it has limitations when applied to many offset inks, particularly heat-set varieties. As previously indicated these inks tend to penetrate the paper fibers deeply and bind strongly, making detachment difficult. As a result, flotation often requires high surfactant dosages and may still leave behind visible specks or discoloration (Luo et al., 2018). The use of the resultant recycled pulp is therefore limited and may require post-treatment such as bleaching or using higher percentages of virgin pulp, limiting the purpose of recycling through increased environmental impact.

Moreover, flotation-based systems typically generate substantial volumes of sludge, containing ink residues, surfactants, and fines. Wastewater from these systems has high chemical oxygen demand, requiring further treatment before discharge (Houssni et al., 2022). In terms of energy, the mechanical repulping and frothing stages are also relatively intensive, adding to the operational costs and environmental burden.

Despite these challenges, flotation systems are well-integrated into existing mills. While improvements such as Sedicell technology, a secondary flotation and fiber recovery system, help increase yield and reduce waste (Fuchs et al., 2017). There remains a need for more sustainable and fiber-friendly alternatives.

Enzymatic De-inking

Enzymatic de-inking represents an innovative approach that employs biological catalysts to facilitate ink removal. Enzymes such as cellulases, hemicelluloses, lipases, and esterases act on the ink binders, coatings, or the paper fiber surface itself, weakening the adhesion between ink and substrate (Pathak et al., 2021). This pre-treatment can significantly enhance ink particle detachment, especially for difficult-to-remove inks like those used in many types of offset printing.

One of the major advantages of enzymatic de-inking is its low environmental impact. Enzymes are biodegradable and require milder process conditions (pH 5–8, 40–60°C), reducing energy input compared to flotation (Singh & Sharma, 2020). Additionally, Kumar and Dutt (2021) discovered that enzymatic de-inking avoids the use of de-inking chemicals; therefore, effluent treatment cost can be

minimized compared to chemical de-inking, thus making these treatments often result in lower sludge volumes and less foaming, simplifying downstream processing.

From a fiber quality perspective, Kumar et al. (2019), claim that enzymatic de-inking leads to less fiber damage compared to conventional methods involving mechanical shear. This helps maintain fiber strength and length, which are crucial for producing higher quality recycled paper. This makes enzymatic de-inking particularly attractive for producing high-grade recycled papers. Further, Ali et al. (2018) state that when combined with flotation, enzymes can enhance overall efficiency by reducing ink particle size and increasing hydrophobicity, making flotation more selective.

However, there are challenges. In a study conducted by Pathak et al., (2021) found out that enzymatic de-inking is sensitive to pH, temperature, and retention time. Moreover, enzyme costs can be high, particularly for tailored enzyme blends needed for specific ink-paper combinations. Industrial adoption has been limited but is growing, driven by increasing demand for eco-friendly processes.

Recent research supports the effectiveness of this approach. Zhang et al. (2020) observed that combining enzymatic pretreatment with flotation improved ink removal by 15–25% for offset-printed paper compared to flotation alone. The enzymatic step enhances hydrophobicity and reduces ink particle size, allowing flotation to function more effectively (Kumar et al., 2021). While cost and reaction time remain challenges, enzyme technologies are becoming increasingly optimized. The hybrid enzymatic-flotation process not only boosts de-inking efficiency but also minimizes chemical usage and fiber degradation, aligning with sustainability goals (Jahan et al., 2018; Torres et al., 2023). Researchers report that enzymatic de-inking significantly enhances the removal of offset inks particularly when used in conjunction with flotation, making it a compelling solution for publication-grade recycling. While the effectiveness of enzymatic de-inking for producing higher quality recycled pulp versus flotation methods alone is a critical factor, environmental concerns also need to be considered.

As previously stated, Conventional flotation de-inking relies heavily on synthetic surfactants and chemical additives, many of which are non-biodegradable and persist in aquatic ecosystems. These compounds contribute to high chemical oxygen demand, sludge formation, and foaming during wastewater treatment, requiring costly and energy-intensive remediation (Houssni et al., 2022). Additionally, synthetic surfactants may release toxic byproducts or microcontaminants that are harmful to aquatic life (Luo et al., 2021).

Enzymatic de-inking presents a more environmentally responsible alternative. Enzymes such as lipases, esterases, and cellulases are biodegradable and function under milder pH and temperature conditions, thereby reducing both chemical input and energy consumption. This results in less aggressive processing, lower COD in effluents, and reduced sludge production (Singh & Sharma, 2020). Moreover, the carbon footprint of enzymatic de-inking is significantly lower due to minimized heating and mechanical energy requirements compared to traditional flotation systems. While enzyme production involves some environmental costs, advancements in microbial fermentation, enzyme immobilization, and reuse are steadily reducing this impact (Kumar et al., 2019). As the technology emerges, ongoing developments promise to make enzymatic de-inking more environmentally friendly. Life cycle assessments have increasingly shown that enzyme-assisted recycling processes align more closely with the goals of green manufacturing and sustainable resource management (Torres et al., 2023). In

essence, enzymatic de-inking offers a viable pathway toward eco-efficient paper recycling, particularly for offset-printed materials that are otherwise resistant to conventional treatment. Together with quality, productivity, and environmental concerns, the economic impact of enzymatic de-inking also needs to be considered.

From an operational standpoint, flotation remains more cost-effective in the short term, given the existing infrastructure and supply chain. Enzymatic processes, while promising, face higher initial costs due to enzyme procurement and process control needs. However, when factoring in long-term benefits such as reduced energy bills, lower sludge disposal costs, and improved paper quality, enzymatic de-inking may offer competitive or even superior cost-performance ratios in high-volume or premium applications (Ali et al., 2018). Therefore, as the industry evolves toward more sustainable and value-driven practices, the strategic adoption of enzymatic de-inking could align both economic and environmental objectives, especially where quality and efficiency are prioritized.

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