Invisible Ink, Visible Risk: A STEAM Exploration of Packaging Ink Transfer onto Food

Kaifang peng [1],Hsin-Hui Wang [2],Chiu, Juei-Yu [1] ,Cheng Ming Lin [3]

[1]National Pingtung University of Science and Technology,

[2]National Tsing Hua University, [3]Ph.D,Aidmics BioTech.CO.,LTD.

kaifangpeng0808@gmail.com

In Taiwan, hot soy milk is often packaged in printed plastic bags, raising food safety concerns about ink migration. This study aims to design a visual ink transfer experiment to guide students in recognizing and reflecting on potential risks in food packaging, thereby encouraging them to voluntarily reduce the use of plastic bags for food storage. We simulate ink transfer through physical friction and immersion in different solvents, investigating factors including water temperature, alcohol concentration, and the effects of solvents with varying polarities on ink migration. This serves as a pilot study for developing exploratory educational materials. The experiment utilized water at varying temperatures (20–95℃), ethanol at different concentrations (20–95%), and diverse food items such as rice wine, soy milk, and cooking oil. A smartphone microscope paired with the ColorAnlz app analyzed hue and saturation changes in ink transferred onto filter paper. Results indicate that ink migration significantly increases with rising water temperature or alcohol concentration. Migration also occurs in rice wine and soy milk, likely due to enhanced ink dissolution from elevated temperature and concentration, the polar extraction effect of alcohol, and pigment release facilitated by hydrogen bonding and hydrophobic-hydrophilic interactions with soy milk proteins. Edible oil exhibited extremely low migration, indicating the ink's polar nature. Even without liquid exposure, repeated contact caused physical peeling. This study serves as an authentic and educational STEAM teaching case, adaptable to the 6E instructional model, aligning with the core principles of SDG 3 (Good Health and Well-being) and SDG 12 (Responsible Consumption and Production)..

Keywords: Food packaging safety, Ink migration, Printed plastic packaging , Smartphone microscope

1. Introduction

Amid growing global concerns over sustainability and food safety, the safety of packaging materials in direct contact with food has become a focal point of international discussion. According to EU Regulation EC No. 1935/2004, Switzerland's Printing Ink Ordinance, and recommendations from the European Food Safety Authority (EFSA, 2024), food contact materials must not release substances harmful to human health under normal conditions of use [1]; Specifically, the migration of low molecular weight substances (<1000 Da) must be below 10 ppb. However, in Taiwan and East Asia, packaging such as printed plastic bags, cup lids, and beverage pouches is still commonly used to directly hold high-temperature beverages like hot soy milk, steamed buns, and milk tea. While this practice is widespread, it has long lacked inspection and attention, harboring overlooked food safety risks. In its 2024 review report, the Food Risk Assessment Agency noted that residual monomers and small-molecule photoinitiators in ink constitute one of the primary migration risks. Their toxicity may include carcinogenicity, endocrine disruption, and increased metabolic burden on the liver and kidneys [1]. International brands like Nestlé and Tetra Pak have long established internal regulations prohibiting the use of BPA-containing developers or non-low-migration systems.

Printing inks are inherently composite materials, typically containing pigments, resins, solvents, and functional additives such as acetate esters, long-chain alcohols, vegetable oil-modified resins, monomers (e.g., styrene), photoinitiators (e.g., benzophenones), dyes (e.g., leuco dyes), and developers (e.g., bisphenol A) [2]. According to solubility theory, polar liquids (e.g., ethanol, soy milk) can dissolve or permeate polar or amphoteric molecules within inks. Additionally, elevated temperatures accelerate polymer chain motion and disrupt microcapsule structures, further promoting the release of ink components—a phenomenon termed "ink migration" [3].

Although the use of "low migration inks" is gradually becoming more widespread, practical understanding of these issues among educators and consumers remains limited. There is also a lack of intuitive methods to explain the scientific principles and potential risks of ink leaching to students or the public. Therefore, this study designed an inquiry-based experiment combining authenticity and educational value. Using commercially available printed plastic bags as samples, we compared four common liquids (hot water, rice wine, soy milk, cooking oil) under varying conditions: temperatures (20°C–95°C), alcohol concentrations, and contact frequencies (single vs. repeated exposure). Through observations and documentation using a mobile app and smartphone microscope, we analyzed the interaction effects of three factors—liquid type, temperature, and solubility—on ink migration.

Key features of this study include: (1) the first systematic investigation of packaging ink migration in everyday Taiwanese contexts; (2) the use of visual experiments combined with mobile technology to make "invisible" risks visible to the naked eye; (3) Establishing an educational module applicable to food safety, materials science, and STEAM education to cultivate students' inquiry skills and risk awareness. We aim not only to alert society to potential hazards in everyday packaging but also to provide a practical model for translating scientific research into educational practice.

2. Experimental Methods

This study utilized rice wine containing 22% alcohol (polar liquid), soy milk containing protein components (exhibiting both polar and amphiphilic properties), blended oil and salad oil (as non-polar controls), and peanut soup (a composite everyday beverage). Additionally, pure water at 20°C (room temperature), 30°C, 65°C, 75°C, and 95°C was used. Alcohol concentration groups were set at 20%, 60%, 75%, and 95% at the same temperature (30°C). Additionally, contact modes were compared between single and multiple exposures (2, 3, 4, 5 wipes) to simulate effects from friction or pressure during packaging handling and storage.

Experimental materials included commercially available printed garbage bags as printed plastic bag samples, filter paper (110 mm diameter, matching petri dish size), petri dishes and lids, heating devices (hot water bottle or induction cooker), temperature-controlled incubator, thermometer, smartphone microscope, and the ColorAnlz color analysis app (for analyzing hue and saturation).

In the experiment, filter paper was first cut or placed flat to fit the petri dish. Printed plastic bags cut to the same size were placed on the filter paper with the printed side facing down. Pure water was heated to the specified temperature. For the alcohol group, solutions were prepared at the designated concentrations. Test liquids (soy milk, rice wine, cooking oil, peanut soup, etc.) were also prepared. The test liquid was gently poured into the petri dish to fully saturate the plastic sheet. The dish was then placed in an incubator or temperature-controlled chamber to maintain the set temperature for 24 hours. After the reaction concluded, the plastic sheet was carefully removed, and the pigment residue on the filter paper was observed.

The degree of ink migration was documented using a smartphone microscope, and ColorAnlz application for quantitative analysis. Hue and Saturation values were measured at three fixed positions on each image, with averages calculated. Hue variations indicated shifts in color components, while Saturation changes reflected pigment concentration alterations. Finally, data variations under different contact frequencies and liquid conditions were compared, with cumulative effects presented graphically.

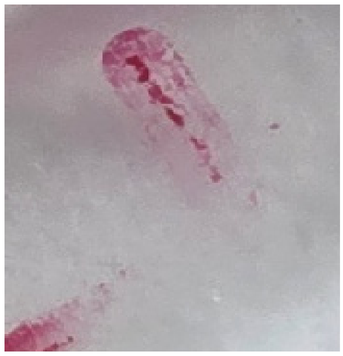

Figure 1: Migrating pigment particles and impurities observed under a smartphone microscope

Observation using a smartphone microscope (Figure 1) reveals distinct pigment particles and impurities released within the migration zone. By capturing hue and saturation data with the ColorAnlz App and conducting ΔE color difference analysis, it was confirmed that ΔE values significantly increased under high temperatures and polar liquids, indicating heightened color variability.

3. Results and Discussion

This study conducted ink migration experiments on printed plastic bags using four common liquids (hot water, rice wine, soy milk, and cooking oil), investigating the combined effects of three factors—temperature, solvent polarity, and contact frequency—on migration outcomes.

(1). Ink Transfer Experiments at Different Temperatures

In the pure water group experiment, as temperature increased from 20℃ to 95℃, pigment migration became significant above 65℃, with high-density pigment deposits and color spots visible on the filter paper surface. As shown in Figure 1, the horizontal axis represents treatment temperature(℃), while the vertical axis displays hue (H) and saturation (S) values. As temperature increased, the Hue value rose sharply after 65℃, reflecting a shift in color components. Saturation values also increased significantly under high-temperature conditions, indicating enhanced pigment concentration and adhesion [5]. This phenomenon relates to accelerated molecular motion due to heat.

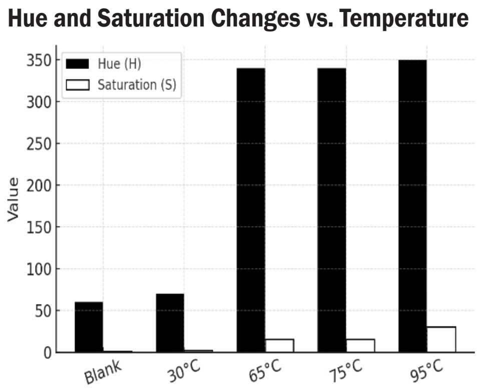

Figure 2: Changes in Hue and Saturation of Ink Migration in the Pure Water Group at Different Temperatures

Elevated temperatures soften polymer chains in both the plastic substrate and ink layer, reducing structural stability [6,7] and loosening the ink layer. Concurrently, microcapsules encapsulating pigments rupture due to expansion, releasing contained dyes. This ultimately causes substantial pigment migration and diffusion onto the filter paper surface [8]. (Figure 2)

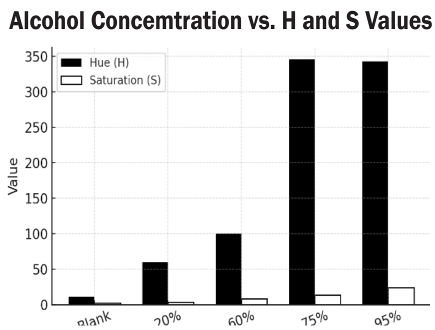

Figure 3: Changes in Hue and Saturation of Ink Migration Across Different Alcohol Concentration Groups

(2). Transfer Printing Experiments with Inks of Different Alcohol Concentrations

Significant ink migration was observed in the alcohol group (treated with 20%-75% ethanol immersion) (Figure 3). The Hue value increased markedly with concentration, reaching saturation at approximately 350 beyond 75%. This result correlates with ethanol's high polarity and low molecular weight, enabling rapid penetration of the ink layer. This process weakens the interfacial forces between the resin binder and plastic substrate while effectively dissolving dyes and other polar components [6.7.9].

(3). Other Daily Food Items

Although peanut soup samples exhibited some saturation variation (approximately 20%), their Hue values remained low (<50). This indicates that despite increased pigment content, the tonal composition showed minimal variation. This phenomenon may be attributed to the adsorption of pigments by sugars and solids. These components likely encapsulate portions of the pigments via hydrogen bonds, causing pigment entrainment and structural alterations. Consequently, this leads to color migration and abnormal saturation [8.9].

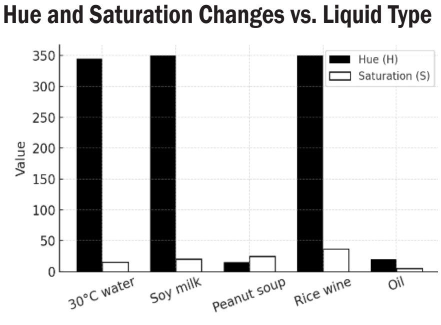

Figure 4: Changes in Hue and Saturation of Ink Migration for Different Test Liquid Groups

The Hue value of the rice wine (22% ethanol) group was close to that of high-concentration alcohol at 350, enabling rapid release of polar dyes onto the filter paper surface. The Hue value of the soy milk group was also near 350, but its Saturation was approximately 15% lower than the alcohol group. This disparity is likely attributed to uneven distribution of ink molecules caused by proteins and emulsifying components in soy milk [9]. The soy milk group exhibited high Hue and low Saturation, presumably due to incomplete dispersion resulting from its protein content and viscosity.

(4). Ink Fading Test Based on Number of Friction times

Based on observations of ink transfer marks on filter paper during experiments, color intensity and area changes serve as evaluation criteria. Repeated contact (2 to 5 times) causes physical peeling and transfer of ink due to friction, even without added liquid, resulting in color fading and diffusion. This indicates that repeated contact or compression between the bag and food during daily use may also cause physical ink transfer. This phenomenon relates to mechanical friction risks and aligns with the EU's technical guidance on ink abrasion resistance [6.7.8] (Figure 5).

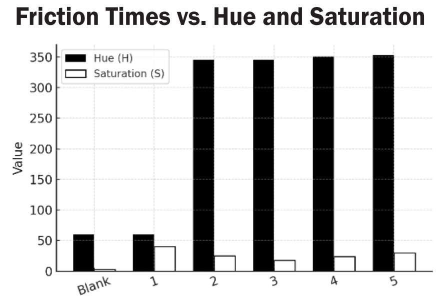

Figure 5: Changes in Hue and Saturation of Ink Migration Caused by Physical Peeling at Different Contact Frequencies (Without Liquid)

4.6E Teaching Model

In this study, experimental procedures and results were further transformed into a STEAM curriculum based on the 6E instructional model, enabling students to learn through hands-on engagement. The 6E process is divided into six stages.

In the “Engage” stage, students may initially be prompted with the question, “Have you ever observed ink transfer from plastic bags stored in the refrigerator?” Such real-life examples can be employed to capture students’ attention and stimulate discussion on potential food safety risks.

In the “Explore” stage, students work in groups to investigate the effects of different liquids (e.g., alcohol, soy milk, oil), varying temperatures, and contact frequencies, while observing the color changes.

In the “Explain” stage, students are guided to interpret the experimental results in order to explain why ink transfers. A smartphone microscope and analysis app are employed to observe the details, analyzing how ink transfers is influenced by polarity, thermal properties, and solvent type.

In the "Engineer" phase, students construct simple observation tools using filter paper, plastic film, and microscopes, create color intensity charts, and use simple instruments such as smartphone microscopes to facilitate observation.

In the "Enrich" phase, the experimental results are connected to broader food safety issues (such as BPA and the 10-ppb limit) and to the significance of SDG 3 and SDG 12, thereby facilitating discussion on global packaging regulations.

In the final "Evaluate" phase, students are required to interpret the data, answer conceptual questions, and use the observed images and data to support their ideas.

5. Conclusion

This study confirms that high temperatures, polar liquids, and contact pressure significantly increase the risk of ink migration. Educationally, this experimental design enables students to visualize potential risks in food packaging and reflect on the safety of daily plastic bag usage, aligning with the core principles of SDG 3 (Good Health) and SDG 12 (Responsible Consumption).

Figure 6: Schematic illustration of ink migration directly from packaging to food [11]

Commercially available printed plastic bags were placed over toast surfaces. Through simulated daily contact scenarios involving friction and heating, ink migration onto the toast surfaces was induced. Subsequently, a smartphone microscope was used for magnified observation, capturing high-resolution images. These images were imported into an image analysis software app for color analysis, yielding data on saturation and hue. The findings were ultimately compiled into visual representations (Figure 6) serving as experimental evidence for this study.

6. References

[1] Eller and Heckman LLP. (2025, January 19). Swiss printing inks ordinance updated. Packaging Law.com https://www.packaginglaw.com/news/swiss-printing-inks-ordinance-updated

[2] Rožić, M., Vukoje, M., et al. Acta Graphica, 28, 137–147-(2017)

[3] Desie, G., & Van Roost, C. Journal of Imaging Science and Technology, 50, 294–303(2006).

[4] Gupta, R. K., Pipliya, S., Karunanithi, S., Eswaran, G. M., Kumar, S., Mandliya, S., Srivastav, P. P., Suthar, T., Shaikh, A. M., Harsányi, E., & Kovács, B. Foods, 13, 3125(2024).

[5] Hunt, R. W. G., & Pointer, M. R. (2011). Measuring Colour(4th ed.). Wiley.

[6] Fried, J. R. (2014). Polymer Science and Technology(3rd ed., pp. 203-272). Pearson Education.

[7] Cussler, E. L. (2009). Diffusion: Mass Transfer in Fluid Systems(3rd ed., pp.1-50). Cambridge University Press

[8] Ghosh, S. K. (2006). Functional coatings and microencapsulation: A general perspective. In Functional Coatings: by Polymer Microencapsulation (pp. 1–28). Wiley-VCH.

[9] Rosen, M. J., & Kunjappu, J. T. (2012). Surfactants and Interfacial Phenomena(4th ed.,pp. 235-245). Wiley.

[10] Ghosh, S. K. (2006). Functional coatings and microencapsulation: A general perspective. In Functional Coatings: by Polymer Microencapsulation (pp. 1–28). Wiley-VCH..

[11] OpenAI. (2023). ChatGPT (Mar 14 version) [Large language model]. https://chat.openai.com/chat