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Innovative Packaging to Life: The Magic of Photochromic and Fluorescent Nano-Inks in Modern Packaging Design as New Era in Consumer Experience

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Abstract
The packaging industry is increasingly exploring innovative approaches that merge functionality with consumer interactivity. However, a significant challenge remains in the limited application of smart nano inks particularly photochromic and fluorescent (FL) inks and sustainable for packaging printed based on water solvent. as functional design elements in packaging, especially for eco-friendly substrates. This research aims to overcome this limitation by developing and evaluating nano-scale photochromic and fluorescent inks based on acrylate resins, with water as the solvent medium, to create smart, sustainable packaging solutions.
Two nano-ink formulations were synthesized and applied to both paper and plastic substrates. Comprehensive analyses including particle size, zeta potential, glossiness, whiteness, and dry rub color fastness were conducted before and after UV exposure. Results showed that fluorescent nano-inks exhibited higher stability (zeta potential −31.34 mV), narrower particle size distribution as nano ink, and better gloss retention compared to photochromic counterparts. Both ink types maintained excellent rub resistance (Gray Scale rating of 5) across all substrates. However, significant UV-induced degradation was observed in whiteness and gloss for all samples, more prominently in photochromic inks. Visual tests confirmed the intended luminescent and color-changing properties of the inks under UV light.
This study successfully demonstrates the feasibility of applying eco-friendly, interactive nano-inks in packaging to enhance both brand identity and consumer engagement. They (PC) (FL) can be applied to preserve the product's identity from counterfeiting. Future research should focus on improving UV resistance and exploring multi-stimuli responsive nano-inks to further elevate smart packaging technologies.

Keywords
Photochromic; Fluorescent; Nano-Ink; Innovative Design; Internet Packaging, Consumer Experience

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Introduction:
In the modern world of packaging, functionality and aesthetics are integral to the success of a product's presentation and the enhancement of consumer experience [1]. One significant innovation in the packaging industry is the use of photochromic and fluorescent inks [2]. These inks are designed to exhibit unique properties that go beyond traditional printing, offering both functional and visual appeal [3]. Photochromic (PC) inks change color in response to light, while fluorescent inks glow under ultraviolet (UV) light, offering packaging designers new tools to create dynamic, interactive, and highly engaging products [4]. This paper explores the fundamentals of photochromic and fluorescent inks, their properties, and the innovative applications they offer in the packaging sector [5].

Statement of the Problem:
The limitations of using special inks (fluorescent and photochromic) in the printing of packaging labels as distinctive features for label design, and how smart nano-inks can be applied in the packaging field

The research problem can be stated in the following questions:
What is the effect of using photochromic and fluorescent inks on printing of packaging label?
How fluorescent and photochromic inks will be applied in innovative designs for packaging label?

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Objective:

The research aims to overcome the limitations of using fluorescent and photochromic inks in printing packaging label by utilizing them as smart, environmental friendly nano inks based on water as a solvent.

Research significance:

The importance of research lies in the global challenges in the field of packaging, through the addition of innovative future technology for printing of packaging labels using smart, environmental friendly nanomaterials that create added competitive value for products. The smart application can be utilized in many areas, providing design insights that are employed to improve the quality of label production within the packaging system. This research will be shared in development of inks industries and safe environmental contamination with high production inks. In addition, this work will be supporting new academic research area in smart inks applications.

Research Hypothesis:

H1: Provide an interactive smart ink that is eco-friendly for the Egyptian packaging market.

H2: Evaluate the effectiveness of applying smart nano inks to packaging materials according to THE COMPLETE TECHNOLOGY BOOK ON PRINTING INKS, 2003.

H3: Florescence inks will be established higher interactive and interesting to printed items.

H4: photochromic inks exhibited nice color changes in presence and absence of UV-light (sun light).

Research Methodology:

The research methodology follows an experimental research approach to study, examine, and evaluate the effect of photochromic smart inks and fluorescent inks used in packaging materials. A smart nano ink will be innovated from eco-friendly materials (acrylate resins) and then applied to a printed label in two parts of the label (two drops of water) A aging test was conducted on printed samples on paper and plastic by exposing them to ultraviolet radiation for a duration equivalent to one year of product exposure in stores.. Standard tests will be conducted to ensure the effectiveness of the nano ink, along with visual c under ultraviolet light to demonstrate the ink's visibility when exposed to UV radiation. Additionally, standard tests (rub resistance tests, gloss tests, and whiteness tests) will be conducted, and all results confirmed the effectiveness of the smart ink for various applications in the packaging field.

Samples and techniques:

1- Two samples of smart ink: photochromic **(**PC) ink and fluorescent (FL) ink.
2- Printed Labels (paper – plastic) and the application of both smart inks on parts of the labels.
3- A lamp UV-induced
4- Dry rub device, a gloss device, and a whitening device.

Theoretical Framework:

Photochromic Inks: A Dynamic Color Change Mechanism

Photochromic inks are a class of inks that change color when exposed to certain wavelengths of light [6]. These inks contain photochromic compounds that are sensitive to light, primarily UV radiation [7]. When the ink is exposed to UV light, it undergoes a reversible chemical change, which results in a shift in the absorption spectrum of the ink, causing a visible color change [8]. This property allows photochromic inks to "respond" to environmental conditions such as light exposure, making them suitable for interactive packaging and smart labels [9].

Figure1. photochromic paste printing on textile

The most common application of photochromic inks in packaging is for security purposes, as they can act as hidden indicators [10]. For example, a label on a product could be printed with a photochromic ink that changes color when exposed to sunlight, revealing a unique pattern or symbol [11]. This type of functionality is valuable for anti-counterfeiting measures, ensuring that products are genuine [12]. Additionally, photochromic inks can be used in product packaging and textile as shown in Figure 1, to create eye-catching designs that change depending on the lighting, enhancing the consumer experience [13].

Fluorescent Inks: The Glow That Captivates:

Fluorescent (FL) inks, on the other hand, are designed to glow under UV light [14]. These inks contain fluorescent pigments that absorb light at specific wavelengths and then re-emit it at longer wavelengths, creating a bright, glowing effect [15]. Fluorescent inks are particularly useful for packaging that needs to stand out in low-light conditions, such as products sold in nightclubs, bars, or under dim retail lighting [16].

Fluorescent inks are often used in combination with other decorative elements to create bold, striking visuals. When illuminated by UV light, the colors appear more vibrant and vivid, providing an additional layer of excitement and interaction for the consumer [17]. The high visibility and unique visual effects of fluorescent inks make them a popular choice for packaging designs intended to capture attention on crowded shelves [18].

Innovative Designing Vision:

The versatility of photochromic and fluorescent inks opens up numerous possibilities for their application in the packaging industry [19]. Some of the key areas where these inks are making an impact include:

Figure 2. Different designs of bottles with created labels

Previous designs are indicated to availability to apply our labels with FL and PC inks on different marketing products as shown in Figure 2.

1.1. Applications of smart systems for branding and consumer interaction

Both photochromic and fluorescent inks are powerful tools for enhancing brand identity and engaging consumers. Packaging designs featuring these inks can offer an interactive experience, where the color of the packaging changes depending on light exposure, or the product is highlighted under UV light. This kind of dynamic design adds an element of surprise and excitement that appeals to consumers, making the product more memorable [20].

1.2. Safety, interactivity, and anti-counterfeiting.

In a highly competitive market, counterfeit goods pose a significant challenge. Photochromic inks offer an innovative solution to combat counterfeiting by embedding security features that are not visible under normal conditions but reveal hidden messages or logos when exposed to UV light or specific environmental triggers [21-22]. These inks are being increasingly used in packaging for high-value products like cosmetics, pharmaceuticals, and luxury goods [23-24]

1.3. Eco-friendly design strategies, sustainability, and recycling

Photochromic and fluorescent inks can also support sustainability efforts. In some cases, these inks can be formulated with eco-friendly materials, making them more compatible with recycling processes [25-27]. Moreover, their ability to function effectively under specific light conditions means that they may reduce the need for additional packaging materials, contributing to more sustainable production practices [28-29].

1.4. Product safety and validation.

In industries like pharmaceuticals and food packaging, safety is paramount. Photochromic and fluorescent inks can be used in safety labels to indicate whether a package has been tampered with or if a product is nearing its expiration date [30-32]. These inks can serve as an indicator for proper storage conditions, such as temperature sensitivity, by changing color when exposed to certain environmental factors, further promoting consumer trust [33].

1.5. Interactive and Promotional Packaging

Interactive packaging is becoming increasingly popular in the marketing sector [34]. Fluorescent inks, in particular, are ideal for creating visually striking designs that stand out in promotional displays or packaging for limited edition products [35]. With the rise of augmented reality (AR) technologies, these inks can be incorporated into packaging that activates AR experiences when scanned with a smartphone or other device, providing customers with an immersive, multi-sensory experience [36].

1.6. Nano-inks as nice performance applications

Nano inks, comprised of nanoscale particles dispersed within a carrier fluid, represent a cutting-edge technology enabling diverse applications from advanced electronics to biomedical devices [37]. These inks leverage the unique properties of nanomaterials, such as enhanced electrical conductivity, tunable optical properties, and increased surface area, allowing for high-resolution printing and precise deposition. For example, metallic nanoparticles like silver or copper can create conductive traces for flexible electronics, while quantum dots can enable vibrant and energy-efficient displays [38]. Further, nano inks incorporating biomolecules or drug-loaded nanoparticles, solvents, and stabilizing agents is crucial in achieving desired ink properties such as viscosity, stability, and printability [40]. The development and refinement of nano inks continue to be a focus of intense research, with ongoing efforts targeting improved performance, lower manufacturing costs, and broader application scopes [41].

In this research, two types of optical active inks, photochromic and florescence, were prepared with two different resins, acrylate-based materials. Photochromic and FL inks was applied in packaging materials substrate to evaluate the behavior of color and printing properties.

2.1. Materials and methods

The photochromic PC and FL pigments was delivered from Dongguan Hongcai Craft Products Co., Ltd, Dongguan City, China. Acrylate resins was received as gift from Ahbar Co., Cairo Egypt.

The label was designed as shown in Fig 3, on Illustrator v. 29.3 and the design was printed on two materials: plastic and paper. The labels were printed on sticky paper 150g and polyester film 40µm with canon Image press c 10000 vp, Japan. Then, a part of the design (two water drops) was covered with photochromic ink prepared from polyacrylic (environmentally friendly). It was also covered with fluorescent ink. Optical tests were carried out by exposure to ultraviolet rays.

Figure 3, shows an innovative design of label.

2.3. Aging process

UV aging was applied according to ASTM D4329 (packaging material) for one year simulation.

2.4. Characterization

DLS was used to determine the mean diameter and zeta potential of the prepared photochromic ink and florescence ink (FL) based on acrylate resins using NICOMP 380 (ZLS, PSS Santa Barbara, CA, USA). The distribution of particle diameter was measured according to scattering laser light through more than 700 incident times.

2.4.1. Glossiness Measurement

Instrument Used: FRU® Gloss Meter as shown in Fig. 4, measurement Angle: 60°, instrument model: FRU GM60, measurement Mode is Standard Gloss Units (GU) with Angle: 60° (Universal angle for semi-gloss surfaces), Measurement Range: 0–200 GU, Accuracy: ±1.2 GU, resolution: 0.1 GU and compliant with: ISO 2813, ASTM D523.

Figure 4. FRU® Gloss Meter

2.4.2. Whiteness test

All photochromic and florescence samples were measured without exposure to light activation. Digital Whiteness Meter, model: WBD-1, as shown in Fig. 5, manufacturer by Shanghai Jinija Scientific Instrument Co., Ltd. Based on the reflectivity of sample surface to standard light source. Light Source is C light source (like average daylight) with Wavelength Sensitivity, 457 nm (blue light). Calibration Method is Manual zero adjustment and correction before each measurement. Measures whiteness degree of paper and plastic materials. All measurements were conducted with calibrated equipment and under standard laboratory conditions.

Figure 5. Digital Whiteness Meter, model: WBD-1

2.4.3.Color Fastness to Rubbing (Dry)

Reference Standard method is AATCC Gray Scale for Color Chan with model, Crock meter – Manual Rubbing Tester as shown in Fig. 6. The evaluation was conducted according to AATCC standards for Color Fastness to Rubbing (Dry). Testing was performed using a manual Crock meter, applying a controlled pressure with a standard cotton rubbing cloth over the printed art paper samples. The degree of color transfer and surface change was assessed using the AATCC Gray Scale for Color Change, with ratings from 5 (no change) to 1 (severe change). Testing conditions are pressure applied: standard Crockmeter setting (9N), number of rubs: 10 cycles, rubbing cloth: standard cotton cloth and testing environment at ambient laboratory conditions.

Fig. 6 Crock meter – Manual Rubbing Tester

3. Results and Discussion

3.1. Innovative methodology for consumer experience

Printed labels with FL and PC nano inks were irradiated with UV-rays as simulation aging. Labels were captured under normal and UV- lamp.

Figure 7 eyes visualization of printed packaging labels with FL inks before and after UV aging under normal and UV-light

As shown in Fig. 7, left side – under UV light (fluorescence visualization) top (before UV aging) exhibited fluorescent inks appear intensely luminous under UV exposure and the aqua green logo and Arabic text display strong blue and green fluorescence. In addition, the glow is uniform and clearly visible, indicating fresh ink with high fluorescent intensity. On the other hand, bottom (after UV aging) presented there is a noticeable decrease in fluorescence intensity. Colors are less vibrant, particularly the green droplet and Arabic text and this fading suggests photo-degradation or quenching of fluorescent components due to prolonged UV exposure.

Right side – under normal light (visual appearance) top row (before UV aging) labels show crisp colors and clear design elements. No visible discoloration, and the ink maintains its original hue. Additionally, Bottom Row (after UV aging) shows, slight fading or discoloration can be seen, particularly in the green and blue tones. The label remains legible, but some loss of visual intensity is present.

The image provides a clear demonstration of how fluorescent inks used in packaging can deteriorate under UV exposure. Smart ink selection, stabilization, and protective measures are essential to preserve both functional and visual integrity of printed packaging over the product's life cycle.

Figure 8 eyes visualization of printed packaging labels with PC inks before and after UV aging under normal and UV-light

As shown in Fig. 8, left side – under UV light, photochromic visualization before UV aging, shows photochromic inks which appear intensely excited under UV exposure and the printed label. Moreover, the printed areas are uniform and clearly visible, indicating nice ink with good photochromic intensity. On contrast, bottom, after UV aging, presented there is a noticeable decrease in photochromic intensity. Colors are less vibrant, particularly the green droplet and Arabic text and this fading suggests photo-degradation or quenching of fluorescent components due to prolonged UV exposure.

Right Side – under normal light (visual appearance) top row (before UV Aging) labels show shine colors and pure design elements. Visible color changes, and the ink continues its original hue. Additionally, bottom row, after UV aging, shows, Slight disappearing or color change can be seen, particularly in the blue area. The label remains legible, but few losses of visual intensity is existing.

Fig. 8 shown the distinguished color of fluorescence ink as luminesce color with phosphoric color emission under UV- light. In addition, photochromic ink exhibits color under UV-lamp. These images confirm the visual light activity of FL printing inks. From the results of Figure 8, all previous hypothesis of the research is realized.

3.2. Particle size for inks

Displayed particle size distributions obtained through Dynamic Light Scattering (DLS), as indicated by the "Intens-Wt Gaussian Distribution". The distributions are presented as histograms. In this test, a diluted concentration of the prepared coating is used and then exposed to ultrasound (laser wavelength 750 nm) to ensure light scattering, as the beam is divided into two parts, one of which is the reference beam and the other falls on the sample, the degree of light scattering is calculated and compared with the beam reference.

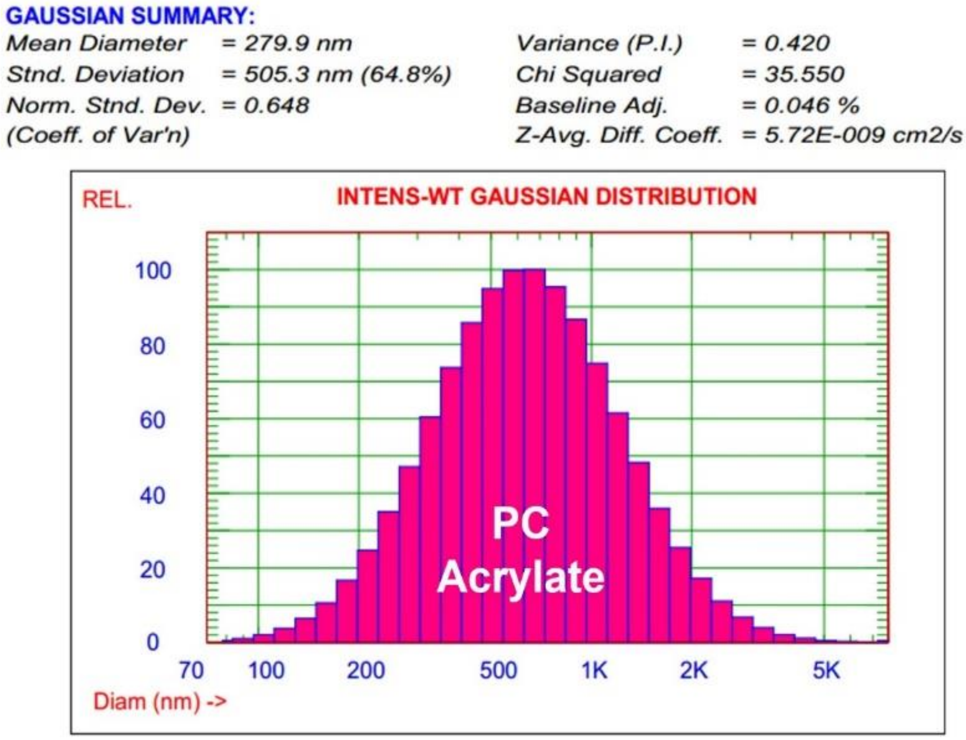
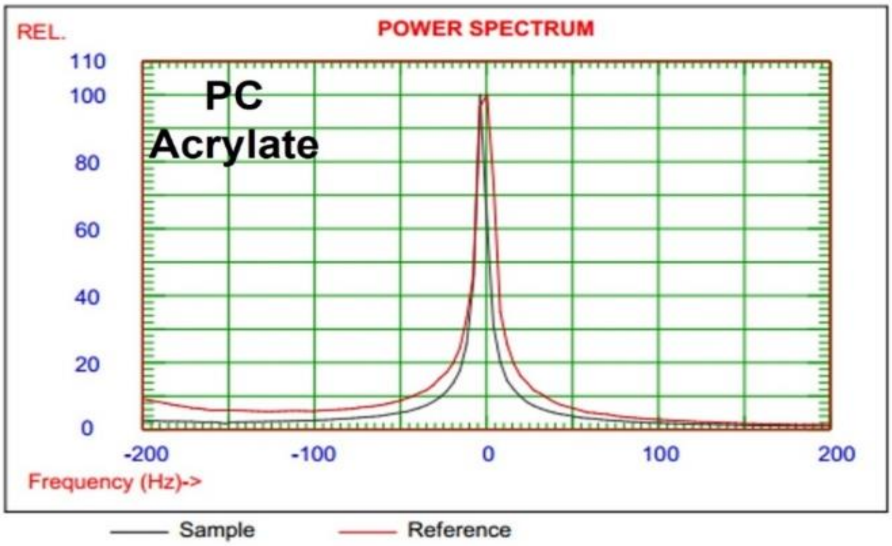


Figure 3. particle size distribution of photochromic nano-inks with acrylate-based resins

In Figure 3. PC Acrylate presence mean diameter: 279.9 nm. This is notably smaller than the mean diameter of the first distribution. This means our prepared inks are nano inks.

3.3.Zeta potential of ink

Zeta potential is a critical parameter that provides information about the stability of inks. The purpose of this test is to measure the degree of stability and homogeneity of the emulsion in the solution. The test is carried out by applying an electric field of 4 mille volts to induce the particles to move between two electrodes and according to the speed of the particle movement; the amount of charge is calculated.



Sample Frequency:	259.31	Hz
Reference Frequency:	261.39	Hz
Cell Current:	0.13	mA (Cond.Factor = 1.92)
Frequency Shift:	-2.08	Hz
Avg. Mobility:	-1.67	M.U.
Half-Width Mobility Dist.	-----	
Avg. Zeta Potential:	-23.94	mV
Half-Width Zeta Pot'l Dist.	-----	

Figure 4. Zeta potential of photochromic nano-inks with acrylate-based resins

As shown in Figure 4, PC Acrylate has an Average Zeta Potential -23.94 mV. This negative zeta potential indicates that the particles have a negative surface charge. Such values are typically at the limit between a semi-stable and instable colloidal system, making the "PC Acrylate" likely to show a medium-term stability for the ink.

GAUSSIAN SUMMARY:

Mean Diameter	*= 249.5 nm*	*Variance (P.I.)*	*= 0.045*
Stnd. Deviation	*= 117.0 nm (21.3%)*	*Chi Squared*	*= 49.250*
Norm. Stnd. Dev.	*= 0.213*	*Baseline Adj.*	*= 0.905 %*
(Coeff. of Var'n)		*Z-Avg. Diff. Coeff.*	*= 8.12E-009 cm2/s*

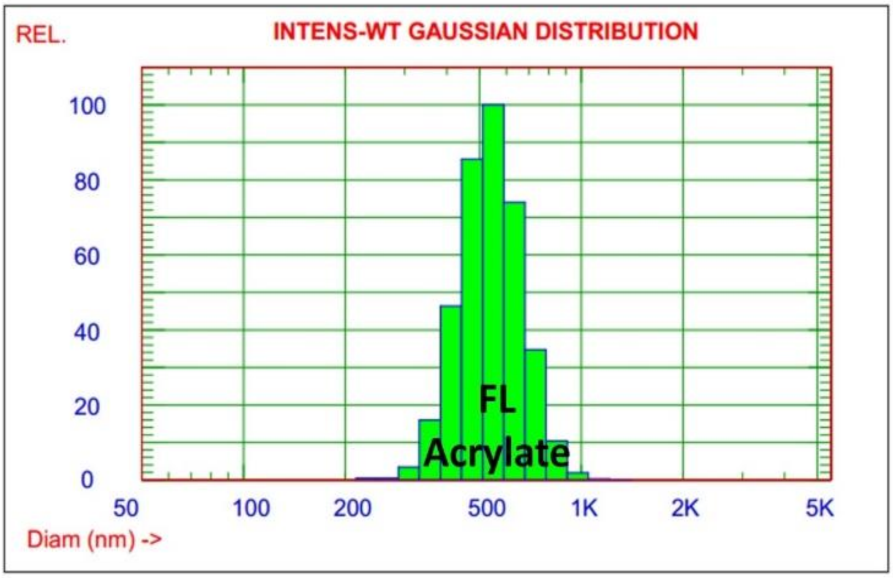


Figure 5. particle size distribution of florescence nano-inks with nitro-cellulose and acrylate-based resins

The particle size distributions show that the FL Acrylate system has smaller particle sizes and a very narrow distribution (monodisperse) as shown in Figure 5.

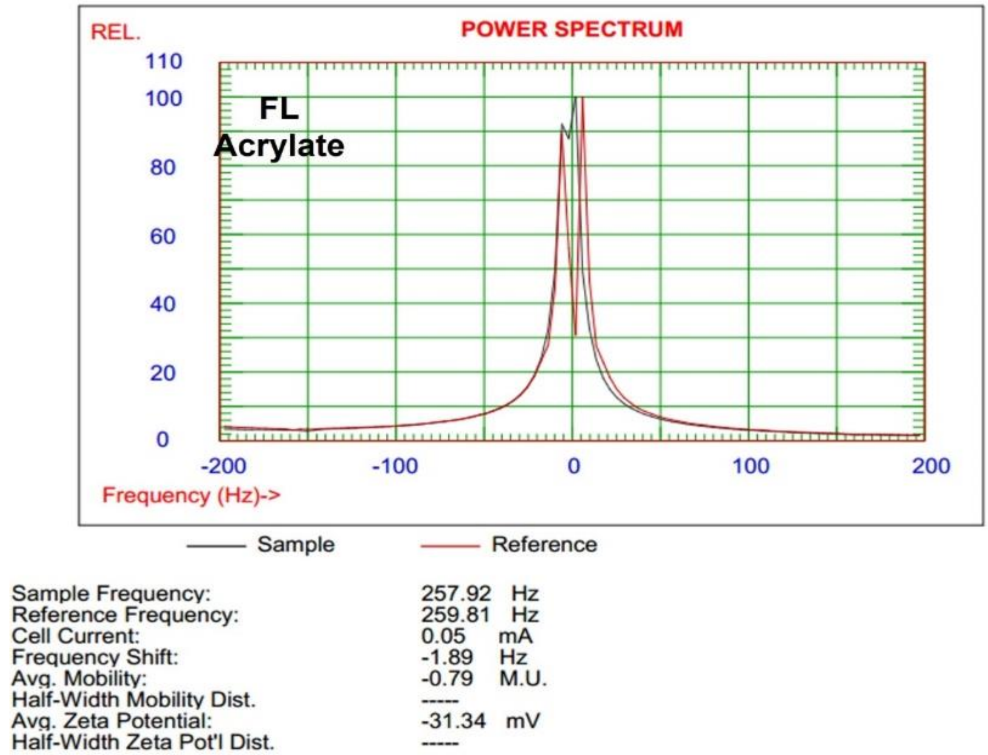


Figure 6. Zeta potential of florescence nano-inks with nitro-cellulose and acrylate-based resins

As presence in Figure 6, Zeta Potential Magnitude for FL Acrylate (-31.34 mV). The zeta potential measurements clearly show that the "FL Acrylate" particles, leading to a greater electrostatic repulsion between particles that give the inks ability to applied on printing machines.

3.4.Glossiness Measurement

This analysis compares the gloss values (GU) of different printed materials (paper and plastic) using two types of inks (PC and FL), both before and after UV treatment. Gloss measurement helps assess surface reflectivity and finish quality, which are essential in material aesthetics and performance.

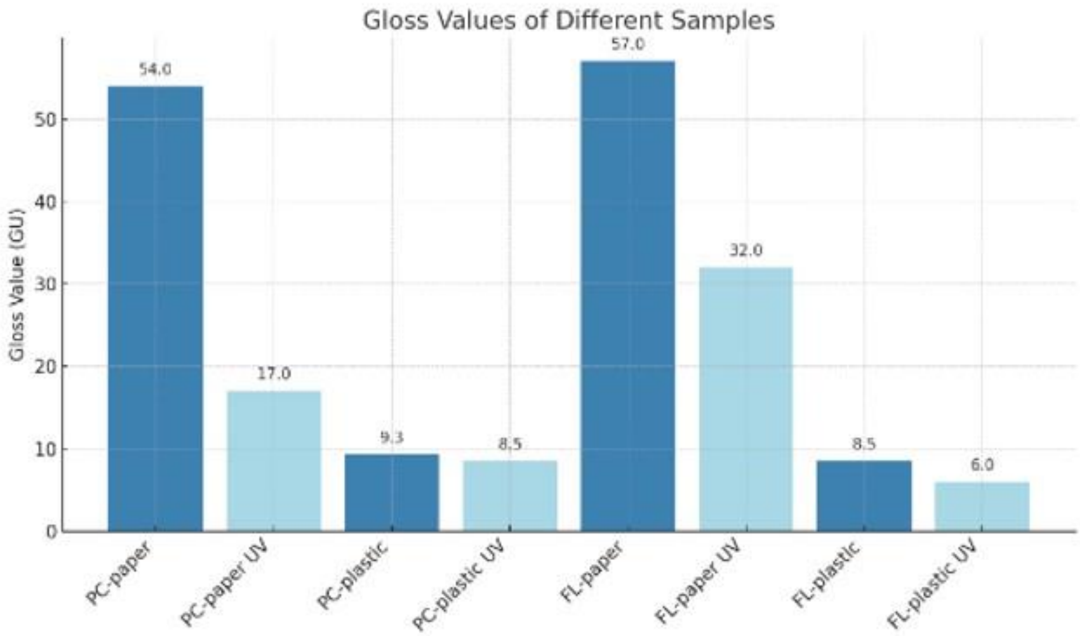


Figure 7. glossy of florescence and photochromic nano-inks with acrylate-based resin on plastic and paper

As presented in Fig. 7 the effect of UV treatment on the glossy of printed supporting paper and plastic films are reported. UV exposure reduced gloss significantly in all cases. PC-paper dropped from 54.0 GU to 17.0 GU. FL-paper dropped from 57.0 GU to 32.0 GU. Plastic samples had smaller drops, but still showed reduction (e.g., FL-Plastic from 8.5 GU to 6.0 GU). This suggests that UV exposure degrades surface reflectivity, likely due to surface roughening, oxidation, or polymer matrix breakdown. Material type differences influence glossy of printed inks. Paper samples consistently showed much higher gloss values than plastic counterparts. This indicates that the printed paper likely has a smoother or more reflective finish compared to the plastic. Printed PC vs. FL, Before UV treatment, printed FL samples had slightly higher gloss than printed PC ones (e.g., FL-paper 57 vs. PC-paper 54). However, FL-paper retained more gloss post-UV than PC-paper (32 vs. 17), suggesting better UV durability of printed FL on paper.

The analysis highlights the clear influence of both substrate and inks type on gloss retention, especially under UV exposure. FL ink and paper substrates outperform their counterparts in maintaining surface gloss, suggesting their preferable use in applications where long-term aesthetic performance is required.

3.5.Whiteness test:

Whiteness significantly decreased in all samples after UV exposure. PC-paper whiteness dropped from 75.1 to 44.9 where, PC-plastic whiteness dropped more drastically from 60.3 to 21.4. FL-paper and FL-plastic also showed significant declines. This indicates that UV radiation causes yellowing or degradation of the material surface, reducing its perceived whiteness — likely due to photooxidative reactions as shown in Fig. 8.

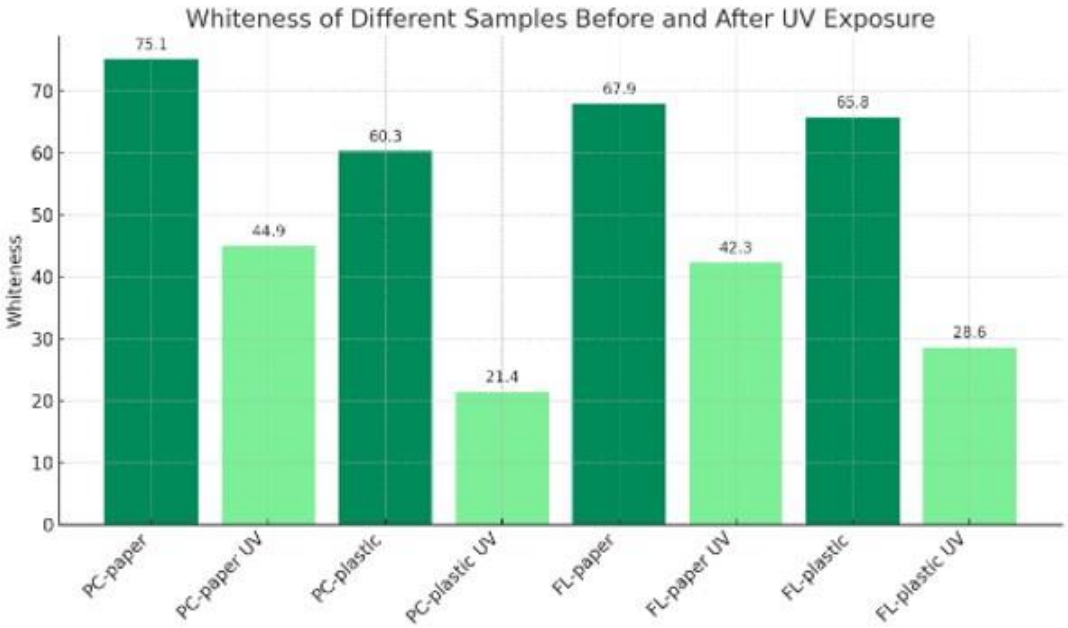


Figure 8. Whiteness of florescence and photochromic nano-inks with acrylate-based resin on plastic and paper

Whiteness significantly decreased in all samples after UV exposure. PC-paper whiteness dropped from 75.1 to 44.9 where, PC-plastic whiteness dropped more drastically from 60.3 to 21.4. FL-paper and FL-plastic also showed significant declines. This indicates that UV radiation causes yellowing or degradation of the material surface, reducing its perceived whiteness, likely due to photooxidative reactions.

Paper samples generally started with higher whiteness compared to plastic samples, especially for PC ink. However, FL-plastic initially showed high whiteness (65.8), closer to paper values, suggesting a more reflective or better surface finish than PC-plastic. In non-UV samples, PC-paper had the highest whiteness (75.1), but after UV exposure, printed FL samples tended to retain whiteness better. For instance, FL-paper retained 42.3, slightly better than PC-paper at 44.9, considering their original values. FL-plastic retained 28.6, better than PC-plastic’s 21.4.

Overall, printed FL seem more UV-stable than printed PC, though both suffered significant whiteness losses. Plastics are generally more vulnerable to UV-induced discoloration compared to papers.

3.6. Color Fastness to Rubbing (Dry)

All samples regardless of substrate (paper or plastic) and whether UV-treated or not received a gray scale rating of 5, the highest possible score. A rating of 5 indicates no perceptible color change or extremely minimal change not noticeable to the eye. Consistently across all tests, no visible color change was observed after dry rubbing. This aligns with the gray scale ratings, confirming the excellent dry rub resistance of both PC and FL printed inks as shown in Table 1.

Table 1. Color Fastness to Rubbing (Dry) of florescence and photochromic nano-inks with acrylate-based resin on plastic and paper

Sample	Substrate Type	Gray Scale Rating	Visual Observation
PC-paper	Printed Art Paper	5	No visible color change
PC-paper UV	Printed Art Paper	5	No visible color change
PC-plastic	Printed Art Plastic	5	No visible color change
PC-plastic UV	Printed Art Plastic	5	No visible color change
FL-paper	Printed Art Paper	5	No visible color change
FL-paper UV	Printed Art Paper	5	No visible color change
FL-Plastic	Printed Art Plastic	5	No visible color change
FL-Plastic UV	Printed Art Plastic	5	No visible color change

No significant difference was observed between Paper and plastic substrates, PC and FL coatings, UV-treated and non-UV-treated samples. This suggests that both inks systems (PC and FL) provide very stable dry rub resistance, and the substrate does not significantly impact performance under these conditions. Surprisingly, even after UV exposure, samples maintained a rating of 5, showing UV aging did not deteriorate their dry rub fastness. This indicates that while UV exposure may affect gloss and whiteness, as seen earlier, it does not weaken the inks' adhesion or mechanical integrity related to surface abrasion.

In conclusion, color fastness to dry rubbing is excellent across all tested inks and substrates. UV exposure does not negatively affect dry rub performance. Both PC and FL inks are highly durable under mechanical dry rubbing, making them suitable for applications requiring handling and surface resistance without aesthetic compromise**.** evaluated the effectiveness of applying smart nano inks to packaging materials as shown in Figs. 7, 8 and Table 1 was carried out as second hypothesis.

Conclusion:

- The integration of photochromic and fluorescent inks into packaging materials presents a wide array of possibilities for brands looking to differentiate themselves in a competitive market. These inks not only provide functional benefits such as anti-counterfeiting and safety indicators, but they also add an element of excitement and interactivity to packaging designs, enhancing the overall consumer experience. As technology continues to evolve, the potential applications for these inks in packaging are bound to expand, offering even more innovative ways to captivate and engage consumers.

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