Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Adhesion And Curing Behaviour Of Coated Plastic Substrates In Hybrid Printing Presses

Kulvir Singh Rohil[1], Sonam Verma[2], Bijender Kaushik[3]

[1.] *Research Scholar, Department of Printing Technology, Somany Institute of Technology & Management, Rewari, Haryana*
[2.] *Assistant Professor, Department of Printing Technology, Somany Institute of Technology & Management, Rewari, Haryana*
[3.] *Assistant Professor, Department of Printing Technology, GJUS&T, Hisar*

The adhesion and curing behaviour of coated plastic substrates in hybrid printing processes are crucial for ensuring high-quality, durable prints specially for flexible packaging applications. This paper aims to optimize substrate performance by investigating ink adhesion and curing efficiency under controlled printing conditions in hybrid printing presses with the combination of Flexo, Gravure and Offset processes. The research systematically evaluates the influence of coating formulations, curing parameters and substrate surface characteristics on overall print quality.

To achieve this, biaxially oriented polyethylene terephthalate (BOPET) films (both coated and uncoated) are subjected to experimental trials assessing ink-substrate interactions. Key measurement methods included surface energy evaluations using ARCOTEST dyne solutions and adhesion strength assessments through Scotch Tape tests. Additionally, UV and electron beam (EB) curing techniques are employed to study polymerization dynamics, ink anchoring behaviour and overall stability of cured prints. By analysing these parameters, the study provides insights into optimizing hybrid printing technologies, advancing substrate engineering and enhancing durability for packaging applications.

KEYWORDS: - Electron Beam (EB), BOPET, Ultra Voilet (UV), Surface energy, Adhesion, Hybrid Printing, Coated Plastic Substrate, Scotch Tape Test

INTRODUCTION

Hybrid printing means printing with the combination of two or more printing processes. Hybrid printing, which integrates Flexo, Gravure and Offset processes into a single system, has revolutionized the printing industry by enhancing efficiency, print quality and substrate compatibility. This approach enables manufacturers to leverage the strengths of each technique, optimizing ink transfer, colour consistency and production speed. Flexible packaging, a major beneficiary of hybrid printing, demands high-performance substrates capable of supporting complex ink adhesion and curing mechanisms. Among these, plastic substrates, particularly biaxially oriented polyethylene terephthalate (BOPET), offer desirable properties such as transparency, thermal stability and barrier performance. However, their inherent low surface energy can hinder ink adhesion, necessitating the use of specialized coatings that improve ink compatibility and durability. The distinction between coated and uncoated substrates is critical for print performance, with coated variants tailored to enhance wettability, adhesion strength and overall process reliability in hybrid printing environments (Kumar & Liu, 2018).

Curing methods play a pivotal role in stabilizing ink on substrates, ensuring long-term durability and resistance to environmental stress. Ultraviolet (UV) curing is widely used due to its rapid polymerization of ink formulations under exposure to UV light, creating robust adhesion while maintaining production speed. Electron beam (EB) curing, in contrast, employs high-energy electrons to initiate crosslinking reactions without requiring photo-initiators, reducing volatile emissions and enhancing adhesion efficiency. Both methods influence ink bonding at a molecular level, affecting factors such as polymerization rate, curing depth and mechanical stability of the printed layer. The choice between UV and EB curing is dictated by substrate properties, desired ink behaviour and the specific requirements of flexible packaging applications. A thorough understanding of these curing processes is essential for optimizing hybrid printing performance and ensuring consistent adhesion across various substrates (Jansen & Mukherjee, 2019).

Surface energy is a key parameter determining ink wetting and adhesion behaviour, particularly on plastic films. Materials with low surface energy often resist ink spread, leading to poor adhesion unless modified through coatings or surface treatment techniques. Measurement tools such as ARCOTEST dyne solutions provide precise assessments of a substrate's wettability, guiding formulation adjustments to improve ink anchoring. Adhesion evaluation methods, including Scotch Tape tests and peel strength analysis, further quantify the bonding efficiency between ink and substrate, ensuring compatibility with lamination and end-use requirements. The interplay between surface energy, adhesion strength and curing parameters defines the overall print quality and durability in hybrid printing. By systematically studying these variables, researchers and manufacturers can refine coating compositions, curing strategies and substrate treatments to advance high-performance printing solutions for flexible packaging (Cork Industries, 2025).

RESEARCH OBJECTIVE

With the advancement of hybrid printing technologies, achieving consistent adhesion and curing behaviour on coated plastic substrates has become a crucial research focus. As printing systems increasingly integrate Flexo, Gravure and Offset processes, optimizing ink adhesion and curing efficiency is necessary to maintain high-quality output in flexible packaging applications. There remain concerns among researchers and industry professionals regarding the impact of coating formulations, curing methods and substrate surface characteristics on overall print durability and performance. To better understand these interactions, standardized measurement techniques such as surface energy analysis, adhesion evaluation and curing behaviour assessments have been studied to facilitate a comparative analysis of different coated substrate configurations.

The objective of this research is to evaluate the adhesion and curing behaviour of coated plastic substrates in hybrid Flexo, Gravure and Offset printing systems by employing quantitative assessments such as ARCOTEST dyne solution tests for surface energy evaluation and Scotch Tape tests for adhesion strength measurements. Additionally, UV and electron beam (EB) curing techniques are analyzed to compare their impact on ink polymerization efficiency and long-term adhesion stability. By systematically studying substrate-coating interactions and curing dynamics, this research aims to refine hybrid printing parameters, enhance ink-substrate compatibility and contribute to the development of advanced methodologies for improved adhesion strength and print quality in packaging applications.

RESEARCH METHODOLOGY

This study employs a structured experimental approach to examine the adhesion and curing behaviour of coated plastic substrates in hybrid Flexo, Gravure and Offset printing systems. By systematically analysing substrate surface characteristics, ink curing mechanisms and adhesion properties, the research aims to optimize printing performance for flexible packaging applications. The selected substrates include coated and uncoated biaxially oriented polyethylene terephthalate (BOPET) films, which undergo surface energy evaluations using ARCOTEST dyne solutions to assess ink wettability and adhesion potential before printing. Ensuring consistency in substrate preparation allows for reliable comparisons of ink bonding strength across different printing conditions.

Printing trials are conducted using COMEXI CI8 a hybrid printing setup, combining Flexo, Gravure and Offset techniques to evaluate ink deposition and adhesion efficiency. Three commercially available inks i.e., Sun Chemical, Toyo Inks and Uflex are used to examine the impact of formulation variations on adhesion performance and curing behaviour. Standardized ink formulations, designed for UV and electron beam (EB) curing, are applied to analyse the influence of coating compositions on adhesion properties. The curing behaviour of printed substrates is then examined under controlled conditions, comparing polymerization rates, ink anchoring stability and environmental resistance between UV and EB curing methods. UV curing involves the use of ultraviolet light to initiate rapid polymerization, while EB curing utilizes high-energy electrons to achieve efficient crosslinking reactions without requiring photo-initiators. This comparative analysis provides insights into optimizing curing parameters to enhance ink durability and adhesion strength.

Adhesion assessments post-printing is performed using Scotch Tape tests to determine ink bonding efficiency and peel strength analysis to evaluate ink-substrate compatibility under mechanical stress. Surface energy measurements taken before and after printing help identify changes in wettability and adhesion characteristics due to coating and curing treatments. The collected data is systematically analysed using statistical methods to identify optimal coating formulations, curing strategies and printing parameters. This research contributes to advancements in hybrid printing technology by refining substrate modifications, improving ink adhesion performance and developing methodologies for enhancing print quality and durability in packaging applications.

DATA COLLECTION & ANALYSIS

Data collection and analysis in this study are conducted systematically to evaluate the adhesion and curing behaviour of coated plastic substrates in hybrid Flexo, Gravure and Offset printing systems. The experimental framework involves assessing ink-substrate interactions through quantitative measurements, including surface energy evaluation, adhesion strength testing and curing efficiency analysis. Substrate preparation and ink deposition are carefully controlled to ensure consistency, while advanced measurement techniques such as ARCOTEST dyne solutions, Scotch Tape tests and curing assessments using UV and electron beam (EB) technologies provide detailed insights into ink bonding and stability. The collected data is analysed using statistical tools to identify trends, optimize printing parameters and refine substrate-coating formulations for improved adhesion and durability in flexible packaging applications.

Table 1, Ink Adhesion Test on Sun Chemical (EB curable Ink)

Radiation Dose (kGy)	Uncoated BOPET (UT/CT)	Coated BOPET (CH/CT)
30	15%	5%
35	13%	4%
40	12%	4%

Table 1, presents adhesion behaviour of Sun Chemical's electron beam (EB) curable ink on biaxially oriented polyethylene terephthalate (BOPET) films, comparing coated and uncoated substrates at different radiation doses (30 kGy, 35 kGy and 40 kGy). Ink adhesion on uncoated BOPET shows a gradual decline from 15% failure at 30 kGy to 12% at 40 kGy, indicating that increased radiation exposure slightly increases the adhesion strength. In contrast, coated BOPET exhibits consistently higher adhesion values, ranging from 5% to 4% failure only, suggesting that the coating modifies surface characteristics in a way that excellent ink bonding efficiency under EB curing conditions. These findings highlight the influence of substrate coatings and curing parameters on ink adhesion, providing essential insights for optimizing coating formulations and curing strategies in hybrid printing applications.

Table 2, Ink Adhesion Test on TOYO (EB curable Ink)

Radiation Dose (kGy)	Uncoated BOPET (UT/CT)	Coated BOPET (CH/CT)
30	16%	6%
35	13%	5%
40	13%	5%

Table 2, presents adhesion behaviour of Toyo's electron beam (EB) curable ink on biaxially oriented polyethylene terephthalate (BOPET) films, comparing coated and uncoated substrates at different radiation doses (30 kGy, 35 kGy and 40 kGy). Ink adhesion failure on uncoated BOPET shows a decline from 16% at 30 kGy to 13% at 35 kGy, maintaining the same adhesion percentage at 40 kGy. This suggests that higher radiation exposure does not significantly affect adhesion beyond a certain threshold. Coated BOPET consistently exhibits lower adhesion failure values, ranging from 6% to 5%, indicating that the coating affects ink-substrate bonding efficiency under EB curing. These findings highlight the role of substrate coatings and radiation dose variations in ink adhesion performance, offering valuable insights into optimizing ink formulations, curing strategies and substrate treatments for improved print quality in hybrid printing applications.

Table 3, Ink Adhesion Test on Uflex (EB curable Ink)

Radiation Dose (kGy)	Uncoated BOPET (UT/CT)	Coated BOPET (CH/CT)
30	17%	6%
35	13%	5%
40	12%	4%

Table 3, presents adhesion behaviour of Uflex's electron beam (EB) curable ink on biaxially oriented polyethylene terephthalate (BOPET) films, comparing coated and uncoated substrates at different radiation doses (30 kGy, 35 kGy and 40 kGy). Ink adhesion failure on uncoated BOPET exhibits a decreasing trend in values, starting at 17% for 30 kGy and reducing to 12% at 40 kGy, suggesting that higher radiation exposure impacts as better ink bonding. In contrast, coated BOPET consistently shows lower adhesion failure values, ranging from 6% to 4%, indicating that the coating modifies the substrate surface in a way that improve ink bonding efficiency under EB curing conditions. These findings highlight the influence of substrate coatings and curing parameters on ink adhesion performance, offering essential insights for optimizing ink formulations, curing strategies and substrate treatments in hybrid printing applications.

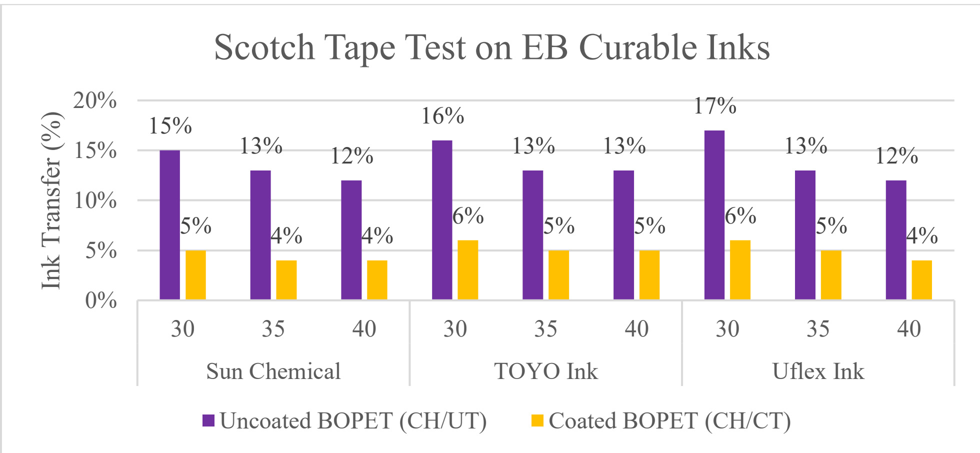

Fig. 1, Comparative Analysis of Ink Adhesion Test On Curable Inks

Fig. 1 presents a comparative analysis of ink adhesion using the Scotch Tape Test on electron beam (EB) curable inks from Sun Chemical, Toyo Ink and Uflex Ink. It evaluates ink transfer percentages on uncoated and coated biaxially oriented polyethylene terephthalate (BOPET) substrates at three different radiation doses 30 kGy, 35 kGy and 40 kGy. The results indicate a general trend where uncoated BOPET consistently exhibits lower ink adhesion compared to coated BOPET across all ink brands and radiation levels. Among the tested inks, Uflex Ink shows the highest ink transfer on uncoated BOPET, with 17% adhesion failure at 30 kGy, while Sun Chemical records the lowest ink transfer on coated BOPET, maintaining 4% at 35 kGy and 40 kGy. Additionally, coated BOPET demonstrates lower ink transfer across all conditions, suggesting that surface modifications introduced by coatings may affect ink bonding efficiency under EB curing. This analysis is significant in understanding the adhesion behaviour of different ink formulations and optimizing substrate coatings and curing parameters for improved print performance in hybrid printing applications.

Table 4, Curing Efficiency on Sun Chemical (EB curable Ink)

Radiation Dose (kGy)	Uncoated BOPET (UT/CT)	Coated BOPET (CH/CT)
30	18%	8%
35	16%	6%
40	16%	6%

Table 4, presents curing efficiency data for Sun Chemical's electron beam (EB) curable ink on biaxially oriented polyethylene terephthalate (BOPET) films, comparing coated and uncoated substrates at different radiation doses (30 kGy, 35 kGy and 40 kGy). Uncoated BOPET demonstrates relatively higher curing efficiency, starting at 18% failure for 30 kGy and reducing slightly to 16% failure at 35 kGy and maintaining the same efficiency at 40 kGy. In contrast, coated BOPET exhibits significantly lower curing efficiency, ranging from 8% failure at 30 kGy to 6% at 35 kGy and 40 kGy, indicating that the coating influences polymerization and ink stabilization under EB curing. These results suggest that coating formulations play a crucial role in curing behaviour, affecting ink crosslinking efficiency and overall print durability. Understanding these curing dynamics is essential for optimizing ink formulations, substrate modifications and curing strategies in hybrid printing applications.

Table 5, Curing Efficiency on TOYO (EB curable Ink)

Radiation Dose (kGy)	Uncoated BOPET (UT/CT)	Coated BOPET (CH/CT)
30	18%	7%
35	15%	6%
40	16%	5%

Table 5, presents curing efficiency data for Toyo's electron beam (EB) curable ink on biaxially oriented polyethylene terephthalate (BOPET) films, comparing coated and uncoated substrates at different radiation doses (30 kGy, 35 kGy and 40 kGy). Uncoated BOPET shows relatively higher curing efficiency, starting at 18% failure at 30 kGy and decreasing to 15% failure at 35 kGy, then slightly increasing to 16% failure at 40 kGy. In contrast, coated BOPET exhibits significantly lower curing efficiency, ranging from 7% failure at 30 kGy to 6% failure at 35 kGy and further reducing to 5% failure at 40 kGy, indicating that the coating influences polymerization behaviour and ink stabilization under EB curing. These results emphasize the role of substrate coatings in modifying curing efficiency and highlight the need for optimized formulation adjustments to enhance ink crosslinking and stability in hybrid printing applications.

Table 6, Curing Efficiency on Uflex (EB curable Ink)

Radiation Dose (kGy)	Uncoated BOPET (UT/CT)	Coated BOPET (CH/CT)
30	18%	7%
35	15%	6%
40	16%	5%

Table 6, presents curing efficiency data for Uflex's electron beam (EB) curable ink on biaxially oriented polyethylene terephthalate (BOPET) films, comparing coated and uncoated substrates at different radiation doses (30 kGy, 35 kGy and 40 kGy). The curing efficiency of uncoated BOPET shows a relatively higher percentage, starting at 18% failure at 30 kGy, decreasing to 15% failure at 35 kGy and then slightly increasing to 16% failure at 40 kGy. In contrast, coated BOPET demonstrates consistently lower curing efficiency, with values ranging from 7% failure to 5% failure, indicating that the coating impacts polymerization behaviour and ink stabilization under EB curing. These findings emphasize the role of substrate coatings in modifying curing efficiency, affecting ink crosslinking and adhesion strength, which is crucial for optimizing ink formulations and curing strategies in hybrid printing applications.

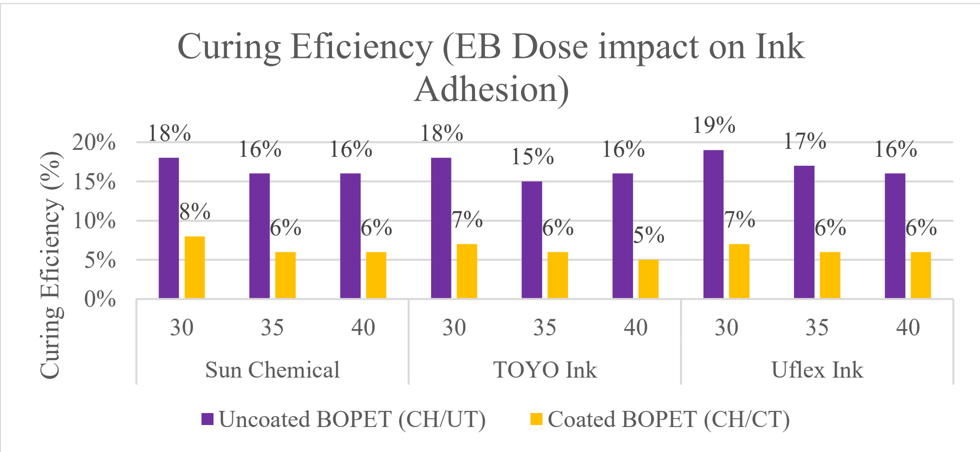

Fig. 2, Comparative Analysis of Surface Energy Test On Curable Inks

Fig. 2, provides a comparative analysis of curing efficiency for electron beam (EB) curable inks from Sun Chemical, Toyo Ink and Uflex Ink on uncoated and coated biaxially oriented polyethylene terephthalate (BOPET) substrates across three radiation doses 30 kGy, 35 kGy and 40 kGy. The data shows that uncoated BOPET consistently exhibits lower curing efficiency across all ink brands, with Sun Chemical 18% failure at 30 kGy, Toyo Ink maintaining similar values and Uflex demonstrating the lower curing efficiency of 19% failure at the same dose. However, coated BOPET surfaces reveal significantly higher curing efficiency, with Sun Chemical showing a decline from 8% failure at 30 kGy to 6% failure at 40 kGy, while Toyo Ink and Uflex follow similar downward trends. These findings underscore the impact of coatings on polymerization behaviour, suggesting that surface modifications may interfere with curing reactions, thereby affecting ink crosslinking efficiency. This analysis provides valuable insights into optimizing ink formulations, refining curing strategies and enhancing substrate modifications to improve adhesion and durability in hybrid printing applications.

RESULTS & DISCUSSION

The adhesion test results indicate that uncoated biaxially oriented polyethylene terephthalate (BOPET) substrates consistently exhibit lower ink adhesion compared to coated substrates across Sun Chemical, Toyo Ink and Uflex Ink. Ink transfer percentages decline with increasing radiation doses, but adhesion remains stronger on coated films. Coated BOPET demonstrates significantly higher adhesion values, suggesting that surface modifications introduced by coatings affect ink-substrate bonding efficiency. Among the tested inks, Uflex Ink shows the highest adhesion performance on coated substrates, while Sun Chemical records the highest adhesion on non-coated surfaces. These results highlight the role of substrate properties and ink formulation in determining adhesion strength in hybrid printing.

The curing efficiency results show that uncoated BOPET achieves consistently higher polymerization compared to coated substrates across all tested inks. Sun Chemical, Toyo Ink and Uflex Ink demonstrate varying levels of curing efficiency, with Uflex showing the lowest stability at 30 kGy. Coated BOPET exhibits notably higher curing efficiency, indicating that the coatings interfere with crosslinking reactions, reducing ink stabilization under EB curing conditions. The decline in curing efficiency at higher radiation doses suggests variations in ink polymerization behaviour, emphasizing the need for optimized formulation adjustments to enhance ink crosslinking and adhesion strength in hybrid printing applications.

CONCLUSION

Uncoated biaxially oriented polyethylene terephthalate (BOPET) exhibited consistently higher ink transfer across Sun Chemical, Toyo Ink and Uflex Ink, with adhesion percentages declining slightly at higher radiation doses. Coated BOPET showed significantly higher adhesion levels, indicating that surface modifications introduced by coatings improve ink-substrate bonding under electron beam (EB) curing conditions.

Uncoated BOPET achieved superior curing efficiency across all tested inks, with higher polymerization rates compared to coated substrates. Coated BOPET consistently demonstrated reduced curing efficiency, suggesting that coatings interfere with crosslinking reactions, impacting ink stabilization and adhesion strength. These findings highlight the need for optimized formulations to enhance ink curing and bonding performance in hybrid printing applications.

REFERENCES

- ASTM International. (2021). Standard test method for evaluating moisture vapor transmission rate (MVTR) of flexible barrier materials (ASTM F1249). ASTM International.
- Banton, R., Casey, B., Maus, C., & Carroll, M. (2018). Adhesion Promotion for UV Coatings and Inks onto Difficult Plastic Substrates. RadTech UV & EB Technology Expo & Conference.
- Bostik. (2025). Adhesive and Lamination Equipment Compatibility Guide.
- Chattopadhyay, A., & Patel, S. (2018). The role of EB curing in improving polymer adhesion to flexible substrates. Journal of Applied Polymer Science, 135(12), 3890–3905.
- Cork Industries. (2025). Adhesion Factors of Surface Energy & Surface Tension.
- DuPont Packaging Graphics. (2019). Advances in polymer substrates for hybrid printing. DuPont R&D Report.
- Gutenberg, J., & Williams, P. (2009). Historical perspectives on gravure printing. Print Tech Publishers.
- Hansen, J. (2020). Sustainability aspects of bio-based coatings for flexible packaging. Green Chemistry & Technology, 12(2), 140–159.
- Huang, L., & Kim, T. (2022). Surface engineering for sustainable packaging: Future directions. Industrial Printing Technology Report.
- Jansen, R., & Mukherjee, S. (2019). Stability and shelf-life considerations for EB-curable flexo inks. Journal of Industrial Chemistry, 36(7), 505–518.
- Kumar, A., & Smith, L. (2021). Ink Adhesion Challenges in Plastic Substrate Printing. Printing Technology Review.
- Kumar, R., & Liu, X. (2018). Advances in hybrid printing technologies using coated substrates. International Journal of Surface Coatings, 24(7), 611–623.