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THE AFTERLIFE OF THE LABEL:

RELEASE LINERS, CIRCULARITY AND THE HIDDEN WASTE STREAM IN PACKAGING

FOT. AVERY DENNISON

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Increasing regulatory requirements, the transition towards a circular economy and rising expectations from brand owners mean that packaging safety is no longer simply a matter of compliance. It has become a key factor in product quality, consumer confidence and long-term business competitiveness. This is why the 16th edition of the Safe Packaging Conference, taking place on 4-6 November 2026 at Zamek Topacz near Wrocław, will once again bring together packaging manufacturers, printers, technology suppliers, brand owners and industry experts to discuss the latest developments shaping the future of safe packaging.

A distinctive feature of this year's programme is the series of optional workshops preceding the main conference. Designed with a strong practical focus, they offer participants the opportunity to develop skills that can be implemented immediately in everyday production and quality management. Sessions dedicated to colour management safety and to the identification and interpretation of NIAS (Non-Intentionally Added Substances) combine expert knowledge with hands-on experience, case studies and direct interaction with specialists. Registration is now open! Visit konferencja.opakowanie.pl to secure your place.

Anna Naruszko, M.Sc. Graduate of the Institute of Printing at Warsaw University of Technology (currently the Department of Printing Technologies, Faculty of Mechanical and Industrial Engineering, Warsaw University of Technology). Editor-in-chief of the monthly trade magazines "Poligrafika" and "Opakowanie", CEO of Alfa-Print Sp. z o.o, publisher of these magazines and of the scientific quarterly "Packaging Review".

Rosnące wymagania prawne, rozwój gospodarki o obiegu zamkniętym oraz coraz wyższe oczekiwania właścicieli marek sprawiają, że bezpieczeństwo opakowań przestaje być wyłącznie kwestią zgodności z przepisami. Dziś jest jednym z najważniejszych elementów budowania przewagi konkurencyjnej. Dlatego 16. edycja konferencji „Bezpieczne Opakowanie", która odbędzie się w dniach 4-6 listopada 2026 r. w Zamku Topacz pod Wrocławiem, będzie miejscem spotkania ekspertów, producentów opakowań, drukarń, dostawców technologii i przedstawicieli firm FMCG poszukujących praktycznych odpowiedzi na najważniejsze wyzwania rynku.

Wyjątkowym elementem tegorocznego programu są poprzedzające konferencję warsztaty, pozwalające uczestnikom zdobyć wiedzę, którą można od razu wykorzystać w codziennej pracy. Szkolenie poświęcone bezpieczeństwu w zarządzaniu barwą oraz specjalistyczny warsztat dotyczący identyfikacji i interpretacji substancji NIAS to okazja do bezpośredniej pracy z ekspertami, dyskusji nad rzeczywistymi przypadkami oraz pogłębienia kompetencji w obszarach, które mają coraz większe znaczenie dla jakości, bezpieczeństwa i zgodności produkcji opakowań. Zapraszamy do rejestracji na konferencja.opakowanie.pl!

Mgr inż. Anna Naruszko. Absolwentka Instytutu Poligrafii Politechniki Warszawskiej (obecnie Zakład Technologii Poligraficznych, Wydział Mechaniczny Technologiczny PW). Redaktor naczelna miesięczników branżowych „Poligrafika" i „Opakowanie", prezes zarządu Alfa-Print Sp. z o. o, wydawcy tych miesięczników oraz kwartalnika „Packaging Review".

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THE AFTERLIFE OF THE LABEL: RELEASE LINERS, CIRCULARITY AND THE HIDDEN WASTE STREAM IN PACKAGING

DRUGIE ŻYCIE ETYKIETY: RELEASE LINERS, OBIEG ZAMKNIĘTY I UKRYTY STRUMIEŃ ODPADÓW W OPAKOWANIACH

ABSTRACT: Packaging innovation is often discussed through visible improvements: lighter bottles, recyclable trays, mono-material films, smarter labels or reduced material use. Yet part of packaging's environmental footprint is created by components that disappear before the product reaches the consumer. This article examines release liners used in pressure-sensitive labelling as one such hidden waste stream. Taking Avery Dennison's AD Circular programme and its partnership with SOPREMA as a case study, the article argues that circularity in packaging should not be understood only as the recyclability of consumer-facing materials. It also depends on collection models, clean material streams, logistics, documentation and credible secondary markets. The conversion of glassine release liners into cellulose wadding for building insulation shows that packaging innovation increasingly takes place not only in materials, but also in the recovery systems that allow those materials to retain value after their first use.
Key words: packaging innovation; release liner; glassine; circular economy; Avery Dennison; AD Circular; label waste; material recovery

STRESZCZENIE: Innowacje opakowaniowe opisywane są najczęściej poprzez widoczne ulepszenia: lżejsze butelki, recyklingowalne tacki, folie monomateriałowe, inteligentniejsze etykiety lub ograniczenie zużycia materiału. Część środowiskowego śladu opakowań powstaje jednak za sprawą komponentów, które znikają, zanim produkt trafi do konsumenta. Artykuł analizuje release liners stosowane w etykietach samoprzylepnych jako przykład takiego ukrytego strumienia odpadów. Na przykładzie programu AD Circular firmy Avery Dennison oraz partnerstwa z SOPREMA tekst pokazuje, że obiegu zamkniętego w opakowaniach nie należy rozumieć wyłącznie jako recyklingowalności materiałów widocznych dla konsumenta. Zależy on także od modeli zbiórki, czystych strumieni materiałowych, logistyki, dokumentacji i wiarygodnych rynków wtórnego zastosowania. Przekształcanie linerów glassine w watę celulozową do izolacji budowlanych pokazuje, że innowacja opakowaniowa coraz częściej dokonuje się nie tylko w samym materiale, lecz także w systemach odzysku, które pozwalają zachować wartość materiału po jego pierwszym użyciu.
Słowa kluczowe: innowacje opakowaniowe; release liner; glassine; gospodarka o obiegu zamkniętym; Avery Dennison; AD Circular; odpady etykietowe; odzysk materiałowy

1. INTRODUCTION

Packaging innovation is usually presented through objects. A bottle becomes lighter. A tray is redesigned for recycling. A flexible film is replaced by a mono-material structure. A label becomes thinner, cleaner, smarter or more compatible with washing and sorting systems. These examples move easily through trade magazines, sustainability reports and conference presentations because they can be shown, photographed and compared. They remain attached to the product and therefore to the consumer's experience.

A quieter part of packaging innovation takes place earlier. It belongs to the converter, the filling line, the warehouse, the logistics chain and the less visible spaces of industrial organisation. It concerns not only the finished pack, but also the materials that make the finished pack possible and then disappear from view.

Release liners are one of those materials. In pressure-sensitive labelling, the liner is indispensable. It protects the adhesive, carries the label through converting and application, and allows the label to be dispensed with speed and precision. Once the

label has been applied, however, the liner has no further role in the packaged product. It is removed before the consumer sees the bottle, jar, tray, carton or pouch. The label remains visible. The liner becomes waste.

This article uses release liner recycling to examine a broader change in packaging innovation. Avery Dennison's AD Circular programme is interesting for a modest but important reason: it makes visible a waste stream that usually disappears into the background of labelling operations. The circular economy in packaging cannot be reduced to the recyclability of what the consumer throws away. It also depends on what happens to less visible streams created along the value chain: liners, matrices, backing papers, films, adhesives, coatings and other materials that are part of packaging production even if they never reach the consumer.

The afterlife of the label is therefore not a marginal technical issue. It is a test of whether packaging sustainability can move beyond the visible surface of the pack and into the material flows that support its production, application and recovery.

2. THE MATERIAL THAT DISAPPEARS

A pressure-sensitive label is sometimes treated as if it were a single printed layer. In reality, it is a laminate structure. It normally includes a face material, adhesive, release coating and liner. The liner, commonly made from paper or film and coated with silicone, enables the label to be stored, converted and applied without the adhesive bonding prematurely to another surface [1]. It is a temporary material with a lasting environmental consequence.

That temporary character explains why liners are easily overlooked. They are not part of the final consumer object. They do not appear in household bins. They do not attract the same public attention as plastic bottles, trays or flexible packaging. They are generated earlier and elsewhere, usually in industrial or commercial settings. Their invisibility is procedural rather than physical: companies see them, handle them and dispose of them, but consumers generally do not.

Yet invisibility does not make the stream negligible. Avery Dennison states that 100,000 labels can generate more than 100 kg of liner waste [2]. The exact quantity depends on label size, liner grammage, construction and application, but the significance of the figure lies less in its precision than in what it reveals. A material that exists only to support another material can become substantial when multiplied across high-volume labelling operations.

The release liner therefore belongs to a category of packaging--related waste that has long sat awkwardly between design and disposal. It is required for efficient application, but it is not valued after application. It is engineered carefully, then discarded quickly. It is essential and unwanted almost in the same moment.

This contradiction gives the liner its analytical value. It forces the packaging industry to confront the difference between the visible sustainability of the finished pack and the less visible sustainability of the system that produces, labels and distributes it.

3. RECYCLABILITY IS NOT CIRCULATION

Glassine and PET are among the most common release liner materials used in pressure-sensitive label constructions [3]. Glassine, in particular, has a strong position in European self-adhesive labelling. It is smooth, dense and highly calendered, which makes it suitable for precise release behaviour and high-speed application. Its technical performance is not the problem. The problem begins after that performance has been delivered.

A material may be recyclable in principle and still fail to circulate in practice. This is one of the central misunderstandings in packaging debates. Recyclability is often presented as if it were an intrinsic material property. In practice, it is also a condition created by collection, sorting, aggregation, transport and end-market demand. A material must be collected, kept clean, accumulated in sufficient volume, transported economically and matched with a recycler capable of processing it. Without these conditions, recyclability remains a technical possibility rather than a functioning recovery route.

The label industry has tried to clarify the technical part of this question. In 2024, CELAB Europe reported the results of a study carried out by the Centre Technique du Papier, which assessed glassine and CCK silicone release liners as pure streams and

concluded that both are recyclable according to European guidelines [4]. This finding is important, but the phrase "pure streams" carries much of the burden. It means that the material must be sufficiently separated and uncontaminated. The material can be recycled, but only if the recovery model preserves its quality after use.

That distinction should shape the way liner recycling is discussed. It is not enough to say that glassine is recyclable. The better question is whether the industry can maintain glassine as a clean stream after application. It is not enough to say that a liner has value. The better question is whether that value can be recovered without excessive friction, cost, contamination or loss of quality.

At that point, circularity stops being a claim printed in a sustainability report and becomes a question of collection bags, storage space, transport routes and clean material streams. This may look like a small operational detail, but in practice it is where much of the environmental claim either holds or not.

4. AD CIRCULAR AS A COLLECTION MODEL

Avery Dennison launched AD Circular in Europe in 2021 as a programme for recycling used paper and filmic label liners [5]. On the surface, the model is simple: users collect liner waste, arrange pickup through a digital platform and the material is directed to recycling partners. The significance of the programme lies in this simplicity. AD Circular treats the liner not as a leftover, but as a managed material stream.

This is where the case becomes useful for analysing packaging innovation. Much packaging innovation still speaks the language of objects: a new substrate, a lighter pack, a better adhesive, a cleaner label. AD Circular belongs to a different type of innovation. Its importance lies not only in proving that a liner can be recycled, but in giving that recycling a route, a procedure and a form of documentation.

Avery Dennison says participants can register, collect used liners for pickup and rely on recycling partners to process the material [2]. The company also states that clients may receive annual certification with quantified proof of the total tonnage of liner recycled [6]. This matters because environmental claims in packaging are moving into an era of evidence. A general statement that waste has been reduced is no longer enough. Companies increasingly need records, quantities, partners, destinations and proof.

The liner, then, becomes data as well as material. Its journey can be recorded. Its disappearance can be made visible. In this sense, the recycling of release liners is part of a wider transformation in packaging sustainability: from intention to traceability.

This does not mean that AD Circular should be read uncritically. Corporate sustainability programmes naturally have a reputational dimension. They help companies tell a story about responsibility, innovation and partnership. But that is not a reason to dismiss them. The more useful approach is to ask whether the story corresponds to an operational system. In the case of AD Circular, the important fact is that the programme connects a known waste stream with a practical collection and recycling model. That is more concrete than a sustainability slogan.

5. THE SOPREMA PARTNERSHIP AND THE OPEN LOOP

The 2025 expansion of AD Circular through a partnership with SOPREMA gives the case a sharper form. Avery Dennison announced that SOPREMA would serve as its primary liner recycling partner across Europe and would collect liners manufactured by any brand or supplier [6]. This detail is important. If a recycling route is limited too narrowly to one producer's own materials, it risks becoming a closed corporate scheme. By accepting liners beyond Avery Dennison's own supply, the programme points towards a recovery pathway that can serve a wider label ecosystem.

The recovered material does not simply return to label production. Avery Dennison states that glassine collected through the joint programme is transformed into cellulose wadding and used for building insulation [6]. Labels & Labeling reported that one ton of glassine liners can insulate up to two attics and may last for the lifetime of the building [7].

This is not closed-loop recycling in the strict sense. The liner does not become a liner again. Packaging waste does not become packaging again. Instead, a specialised industrial waste stream is redirected into a construction material with a longer functional life.

There is a temptation to see this as a weakness. Closed loops have an appealing clarity. Bottle to bottle. Paper to paper. Packaging to packaging. The image is clean and memorable. But industry rarely moves with the neatness of diagrams. Materials often find their most credible second life outside the sector in which they began. If recovered glassine can replace virgin material, avoid disposal and enter a durable application, then the open loop may be environmentally meaningful even if it is conceptually less elegant than a closed-loop model.

The language used to describe such solutions should therefore be precise. It would be too strong to claim that this model solves label waste. It would also be too dismissive to treat it as mere downcycling without further examination. The more accurate description is that AD Circular and SOPREMA create an open-loop recovery pathway for a previously difficult material stream. That is a narrower claim, but a stronger one.

In sustainability communication, the narrower claim is often the more credible one.

6. REGULATION AND VALUE-CHAIN RESPONSIBILITY

The regulatory background gives this discussion additional urgency. Regulation (EU) 2025/40 on packaging and packaging waste entered into force on 11 February 2025 and will generally apply from 12 August 2026 [8]. The European Commission presents the regulation as part of a wider attempt to reduce packaging waste, improve resource use and support a low--carbon circular economy [9]. The Regulation also strengthens the expectation that packaging placed on the EU market should be designed for recyclability within the coming decade [8].

Release liners are not the obvious public face of this regulatory shift. They are not the items photographed on beaches or pulled from urban litter bins. They do not belong to the household drama of sorting, rinsing and separating. Yet this is exactly why they matter. If packaging circularity is understood only through consumer disposal, the industry will continue to miss important upstream and midstream waste flows. If it is understood across the value chain, liners become visible.

FOT. AVERY DENNISON

The label's afterlife therefore belongs to the future of packaging itself. It asks whether circularity is merely a property claimed by a finished pack, or whether it is a discipline applied to the material flows behind that pack.

This broader view changes the meaning of responsibility. It is no longer enough for a brand owner to ask whether the final pack can be recycled by the consumer. It must also ask what waste is generated in producing, decorating and labelling that pack. It must ask whether backing materials are segregated, whether matrices are recovered, whether adhesives interfere with recycling, whether claims can be documented and whether hidden material streams have viable destinations.

The release liner is therefore a small but revealing object. It shows how circularity expands from the pack to the

packaging process. It also shows why the next generation of sustainability claims will be judged not only by material composition, but by evidence of movement through a functioning recovery route.

7. FROM PACKAGING OBJECT TO MATERIAL FLOW

The most interesting thing about release liner recycling is that it changes how the package itself is understood. A package is not only a container, surface or communication device. It is also the visible outcome of a chain of materials, machines, decisions and residues. A label may be applied in a second, but that second depends on paper mills, silicone coatings, adhesives, die-cutting, dispensing equipment, waste handling and, increasingly, recycling logistics.

This is where the Avery Dennison case has broader significance. The company is not simply offering a more sustainable product. It is participating in a redefinition of what packaging innovation means. Innovation is not only the moment when a new material is introduced. It is also the moment when an old waste stream is given a reliable route out of disposal.

CELAB Europe's interactive map of solution providers makes the same point from another angle. The map is intended to help companies find organisations able to collect or recycle used liner and matrix waste [10]. This is not spectacular. It does not look like a new bottle or a new label. Yet it may be exactly the kind of practical tool on which circularity depends. A recyclable stream without a collector is not yet a circular stream. A material with theoretical value but no recovery route remains, in operational terms, waste.

This is why the label industry matters beyond its apparent size. Labels carry branding, legal information, barcodes, batch numbers, warnings, recycling instructions and, increasingly, digital identifiers. They are small, but they organise the relationship between product, producer, regulator, retailer and consumer. If labels have become a functional layer of packaging systems, then liner recovery asks whether the material flow behind that function can also be made responsible.

The label remains on the product. The liner reveals whether the production system has a plan for what it removes.

8. LIMITS, FRICTIONS AND CREDIBILITY

The open-loop pathway represented by AD Circular and SOPREMA has clear strengths, but it also has limits. A serious assessment should not hide them. It is precisely by acknowledging the limits that the case becomes credible.

First, the model depends on clean and relatively concentrated material streams. CELAB's recyclability findings refer to pure streams, and purity is not a minor operational detail [4]. It requires segregation, discipline and awareness at the point where the waste is generated.

Second, transport matters. Liner waste must be stored, collected and moved. If collection routes are inefficient or volumes are too small, the environmental benefit may be weakened. The existence of a recycling route does not automatically guarantee an optimal environmental outcome in every local context.

Third, access may be uneven. Large converters, major brand owners and high-volume label users are more likely to generate predictable quantities of liner waste. Smaller companies may have less space, less administrative capacity and weaker leverage in waste contracts. A system that works well for large users may still need adaptation before it becomes genuinely accessible across the market.

Fourth, open-loop recycling depends on the stability of the receiving sector. If recovered glassine is used in building insulation, the viability of the route is partly tied to demand, specifications and economics in construction. That does not invalidate the solution. It simply means that circularity is never purely internal to packaging. It depends on other industries as well.

These frictions do not make the case weaker. They make it more useful. They show that circularity is not achieved by declaring a material recyclable. It is achieved through coordination, collection discipline, material purity, transport efficiency and credible end markets. Packaging innovation, in this sense, becomes less about novelty for its own sake and more about the management of material value after use.

9. CONCLUSION

Release liners are easy to ignore because they are designed to vanish. They do their work before the consumer arrives. They support the label, then leave the visible life of the package. Yet this disappearance is precisely why they deserve attention. They reveal the hidden material life of packaging.

The case of Avery Dennison's AD Circular programme and its partnership with SOPREMA shows how such a material can be moved from disposal into a managed recovery pathway. Used glassine liners are collected, documented and transformed into cellulose wadding for building insulation. This is not a perfect closed loop and should not be described as one. It is an open-loop route with practical promise, operational limits and wider conceptual importance.

That importance lies in the way the case changes the object of packaging innovation. The future of sustainable packaging will not be decided only by the bottle, tray, carton or label that reaches the consumer. It will also be decided by the materials that never do: the backing paper removed on the line, the matrix left after die-cutting, the adhesive that helps or hinders recycling, the database that records what was collected, the recycler willing to accept a clean stream, the secondary market able to use it.

The label's afterlife therefore belongs to the future of packaging itself. It asks whether circularity is merely a property claimed by a finished pack, or whether it is a discipline applied to the material flows behind that pack.

The answer will not be found on the shelf alone.

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ANALYSIS OF THE EFFECT OF PRINTING SUBSTRATES ON THE QUALITY OF LABELS, PRINTED DIGITALLY BY THE INKJET METHOD

ANALIZA WPŁYWU PODŁOŻA DRUKOWEGO NA JAKOŚĆ ETYKIET DRUKOWANYCH CYFROWO NATRYSKOWO

ABSTRACT: In the paper, the analysis of the impact of the type of the printing substrate on the quality of labels, produced by the method of digital ink jet printing method in hybrid machine, was discussed. Three types of materials were analysed: self-adhesive film, self-adhesive coated paper and textured decorative paper. The assessment included relative contrast, area of reproducible colors (gamut) and dot gain. The obtained results showed that the best properties of image and color reproduction were ensured by self-adhesive film and coated paper which reached the highest values of contrast and the highest color gamut. The decorative paper, in spite of its high esthetic values, was characterized by a lower quality of colour and details' reproduction. The studies have confirmed that the type of substrate is one of the key factors, affecting the quality of the labels, printed by the inject technology.
Key words: inkjet printing, self-adhesive labels, printing substrates, colour gamut, relative contrast, increase of tonal value

STRESZCZENIE: W artykule przedstawiono analizę wpływu rodzaju podłoża drukowego na jakość etykiet wykonanych metodą cyfrowego drukowania natryskowego w maszynie hybrydowej. Zbadano trzy rodzaje materiałów: folię samoprzylepną, papier samoprzylepny powlekany oraz papier ozdobny fakturowany. Ocenie poddano kontrast względny, obszar barw odtwarzalnych (gamut) oraz przyrost wartości tonalnej. Uzyskane wyniki wykazały, że najlepsze właściwości reprodukcji obrazu i barw zapewniają folia samoprzylepna oraz papier powlekany, które osiągnęły najwyższe wartości kontrastu i największy gamut barwny. Papier ozdobny, pomimo wysokich walorów estetycznych, charakteryzował się niższą jakością odwzorowania barw i szczegółów. Badania potwierdziły, że rodzaj podłoża jest jednym z kluczowych czynników wpływających na jakość etykiet drukowanych technologią inkjetową.
Słowa kluczowe: drukowanie natryskowe, inkjet, etykiety samoprzylepne, podłoża drukowe, gamut barwny, kontrast względny, przyrost wartości tonalnej

INTRODUCTION

The contemporary market of label production is characterized by a considerable diversification of the employe printing technologies, and the dominating position is occupied by the analog techniques. In particular, flexography is a basic method of producing the labels, accounting for about 40 – 45% of the total production, especially in respect of the medium and high print circulation. Offset also has a significant participation whereas the techniques such as rotogravure, play a supplementary function in the selected segments of the market. At the same time, we may observe a dynamic development of the meaning of digital printing, the share of which – in label production – is currently equal to ca. 25-30% in terms of value, with the simultaneous lower participation of volume (ca. 10%) [1].

As it was already mentioned, flexography is the most popular printing technology in production of labels. Flexographic

machines are rotational devices where there are employed the flexible relief plates and inks with a low viscosity. Once, the discussed technology was characterized by a weak quality of prints what was eliminated owing to photo-relief high-resolution plates. It was the direct reason for withdrawal of intaglio (engraving) printing in production of packaging [2].

In the field of digital technologies, inkjet printing plays a special role; it is one of the main directions of development of the modern packaging printing. In spite of the fact that its participation in the total volume of label production remains relatively low, the mentioned technology is characterized by the highest growth dynamics and the increasing meaning in the application which require short series, personalization and printing of variable data. In the industrial practice, the inkjet technology functions more and more frequently as a component of hybrid systems, combining the advantages of analog and digital technologies [3].

The essence of inkjet printing is a contactless application of ink drop on the substratum, using the specialistic printing heads which constitute the key element of imaging system. The mentioned heads contain hundreds and even thousands of micronozzles, by the mediation of which the ink is precisely dosed in a form of single drops, creating the image of the surface of print material. Depending on the method of drop generation, there are distinguished few types of inkjet technology, including – as the most important ones – thermal and piezoelectric systems.

In the industrial applications, including label production, the piezoelectric heads are dominating. Their functioning is based upon the piezoelectric phenomenon, consisting in deformation of piezoelectric material as affected by the applied electric voltage what leads to change in the volume of ink chamber and ejection of ink droplet from the nozzle. Contrary to thermal nozzles where the ejection of droplet is implemented as a result of local warming up of the ink and generation of bubbles (bubblejet), the piezoelectric solutions do not require the increased temperature; it enables application of different types of inks, including the photo-hardening (UV) and the solvent-based ones [4-5].

From the viewpoint of label applications, piezoelectric technology is characterized by a high precision of forming the droplets, possibility of controlling their volume, high durability of heads and compatibility with different printing substrates, including non-absorptive materials (films, plastics, metallized laminates). The mentioned factors make that inkjet printing finds a wide application in production of high-quality labels, especially in the sectors, requiring production flexibility and short time of orders' implementation.

The development of inkjet technology is strictly connected with the activities of the leading producers of printing machines who offer the completely digital inject systems as well as hybrid solutions. The most important producers in this sector include, inter alia, EFI, Epson, Canon and also, producers of hybrid machines such as Gallus (Heidelberg), Durst or Mark Andy who integrate inkjet modules and flexographic lines. The discussed solutions facilitate combination of high-quality analog printing and elasticity and functionality of digital technology what is the response to the current requirements of the market [6 – 9].

Reassuming, inkjet printing is nowadays one of the key technologies, shaping the future of label production, offering unique possibilities in the field of quality, personalization and adaptation to differentiated printing substrates.

Apart from the inkjet technology used in printing of labels, there are also employed electrophotographic devices which may be found in the offer of the companies such as Konica Minolta, basing upon the dry toners, or of HP – owner of Indigo technology. The characteristic feature of Indigo machines includes printing with the use of liquid toners, owing to which the prints seem to be more matt, therefore, their quality is approximate to those ones, made by offset technology.

The additional improvement of the quality of electro-photographic prints is ensured by varnishing process. Function of varnish may be played by a transparent toner which, besides aesthetic values, protects the print from mechanical damages and renders the barrier properties. It refers to the prints obtained from the machines, containing dry as well as liquid toner [10].

THE AIM OF THE STUDIES

The purpose of the studies was to compare the labels, produced on various substrates, using hybrid machine [11].

The equipment employed in the experiment makes the prints digitally in seven colors and in white color, with the resolution equal to 1200 dpi. Additionally, it contains a flexographic part, serving for improvement and processes of in-line converting. In the studies, the differentiated label substrates were used; they differed in the materials structure as well as in utility properties.

One of the employed materials was a self-adhesive uncoated paper with grammage of 90 g/m^2, characterized by a distinct, decorative texture of surface with a regular geometric structure. The substrates of this type are classified as materials with the increased esthetic values and are employed, first of all, in the applications, requiring obtaining the visual effect, associated with the premium products. The structural surface affects the way of color and image details' reproduction what may result in limitation of the homogenous ink coverage; however, it increases simultaneously the visual attractiveness of the print. The substrates of the mentioned type are used in the labels of luxury products.

TAB.1. THE MEASUREMENTS OF THE RELATIVE CONTRAST

	C	M	Y	K
Self-adhesive film	20%	14%	10%	18%
Self-adhesive paper	20%	14%	10%	18%
Decorative paper	10%	13%	8%	12%

The second analysed substrate was self-adhesive coated paper, with the grammage of 65 g/m^2, with a smooth, satin-like surface. The layer of coating ensures more controlled penetration of the print ink what results in a high quality of the image reproduction and good reproduction of details and colors. The discussed material s also characterized by good application properties – elasticity and capability of adapting to uneven and curved surfaces. Owing to this fact, it finds a wide application in marking of the products endangered to impact of environmental factors such as humidity, or variable atmospheric conditions. The coated substrates are generally used in food, cosmetics and pharmaceutical industries where the aesthetics as well as stability of the label is required.

Another applied material was a self-adhesive foil substrate on the basis of polypropylene, with grammage of 50 g/m^2. Unlike papers, polymer materials are characterized by a high resistance to the effect of mechanical factors, humidity and chemical substances such as oils or detergents. Owing to this property, they are employed in labeling of the products intended for long storage, transport and use in difficult operating conditions. A smooth, nonabsorptive surface of film affects the specificity of printing process, requiring the appropriate choice of inks and technological parameters. At the same time, it ensures the possibility of obtaining good-quality reproduction of graphical signs and high durability of print. Foil substrates

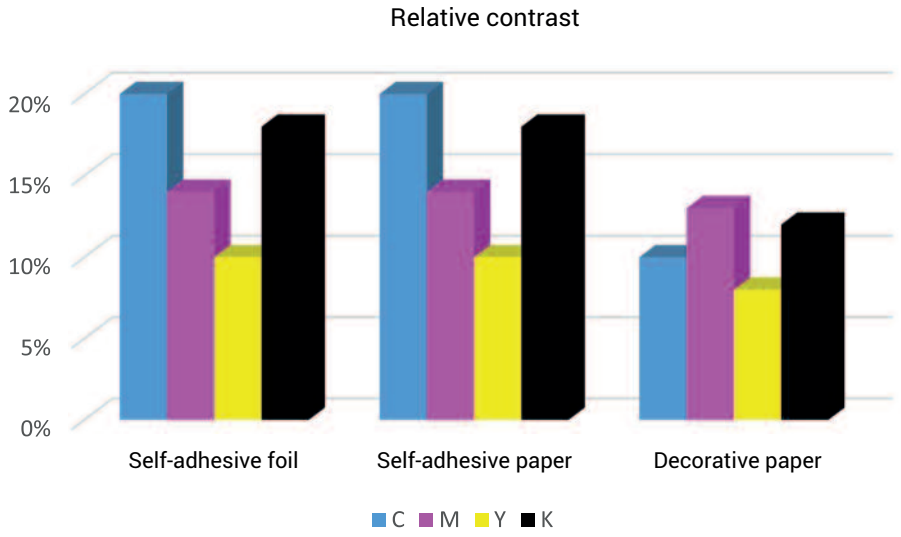

FIG.1.THE RELATIVE CONTRAST OF THE OBTAINED PRINTS

are widely employed in the food, cosmetics, pharmaceutical and chemical sectors, especially in the case of the products utilized under the conditions of the increased humidity or being endangered to the contact with liquid substances.

EXPERIMENTAL

The quality of the digital prints is assessed by the parameters such as, inter alia: span of the space of colors, increase in tonal value and, also, contrast of the print [12]. The mentioned properties of the prints have been measured within the frames of the experiment carried out for the needs of the present paper.

RELATIVE CONTRAST

The measurement of the relative contrast of the performed prints made on three types of paper was one of the conducted tests.

On the grounds of the obtained results, the diagram was developed (Fig.1).

The relative contrast is very similar as all componentials on foil as well as on self-adhesive paper and is found within the limits of 10% (Yellow) – 20% (Cyan). The mentioned values differ significantly from the results obtained on the textured decorative substratum where we observe the range of 8% (Yellow) – 13% (Magenta). As the relative contrast should be the highest possible, it should be stated that in the present study, the textured substratum is characterized by the worse properties as compared to the remaining analysed materials.

GAMUT OF THE PRINTS

The successive parameters, examined in the experiment, was gamut, i.e. the area of colors of the reproducible prints. The

TAB.2. THE RESULTS OF THE MEASUREMENTS; VALUES FROM ISO STANDARD AND DELTA E

		Results of measurements			Values acc. to ISO			ΔE
		L	a	b	L	a	b	
Self-adhesive film	C	51	-40	-53	57	-44	-51	7
	M	52	76	-4	48	82	-3	7
	Y	89	-7	95	93	-5	104	10
	R	52	66	60	48	75	55	11
	G	46	-87	27	49	-77	33	12
	B	17	29	-56	21	22	-54	8
Self-adhesive paper	C	49	-39	-50	57	-44	-51	9
	M	50	73	-3	48	82	-3	9
	Y	85	-5	87	93	-5	104	19
	R	49	65	58	48	75	55	10
	G	44	-80	25	49	-77	33	10
	B	17	28	-54	21	22	-54	7
Decorative paper	C	51	-29	-49	57	-44	-51	16
	M	56	63	-1	48	82	-3	21
	Y	87	-5	77	93	-5	104	28
	R	51	62	49	48	75	55	15
	G	44	-68	20	49	-77	33	17
	B	23	19	-46	21	22	-54	9

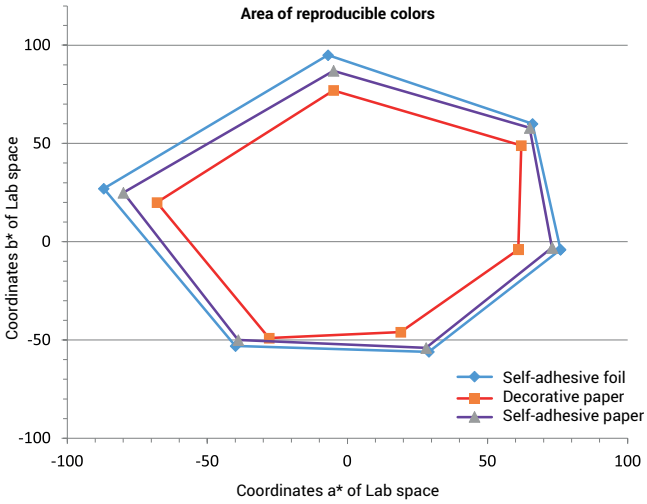

FIG.2. THE AREA OF THE REPRODUCIBLE COLORS

measured values are given in Table 2. Additionally, there were considered the reference values, specified in standard ISO 12647-2 what facilitated their direct comparison in the further analysis. In order to increase the readability of the differences, ΔE values were also presented. Moreover, the diagram, illustrating the area of reproducible colors on the examined substrates was also developed.

The greatest area of reproducible colors was obtained for the prints of self-adhesive foil. Very similar results were obtained for the print on self-adhesive paper. On the other hand, the print produced on decorative substratum is characterized by the decisively lowest gamut what should be recognized as an undesired result. The area of the reproducible colours should be the possible widest. As compared to the requirements of ISO 12647 standard, the values obtained for the print on self-adhesive foil reveal the greatest conformity what is also recorded, to the same extent, in the case of self-adhesive paper. The print of decorative substratum is characterized by values,

TAB.3. INCREASE OF TONAL VALUE

C	100%	19,6%	19,3%	12,00%
	75%	16,3%	15,5%	10,90%
	50%	11,9%	11,4%	9,10%
	25%	6,9%	6,4%	6,00%
	10%	3,5%	3,2%	3,30%
M	100%	14,5%	14,7%	10,30%
	75%	12,2%	11,9%	9,40%
	50%	9,2%	9,0%	7,80%
	25%	3,5%	5,4%	3,30%
	10%	3,0%	2,9%	2,90%
Y	100%	9,6%	10,0%	8,30%
	75%	8,7%	9,1%	7,50%
	50%	7,3%	7,4%	6,30%
	25%	4,8%	5,0%	4,40%
	10%	2,7%	2,8%	2,60%

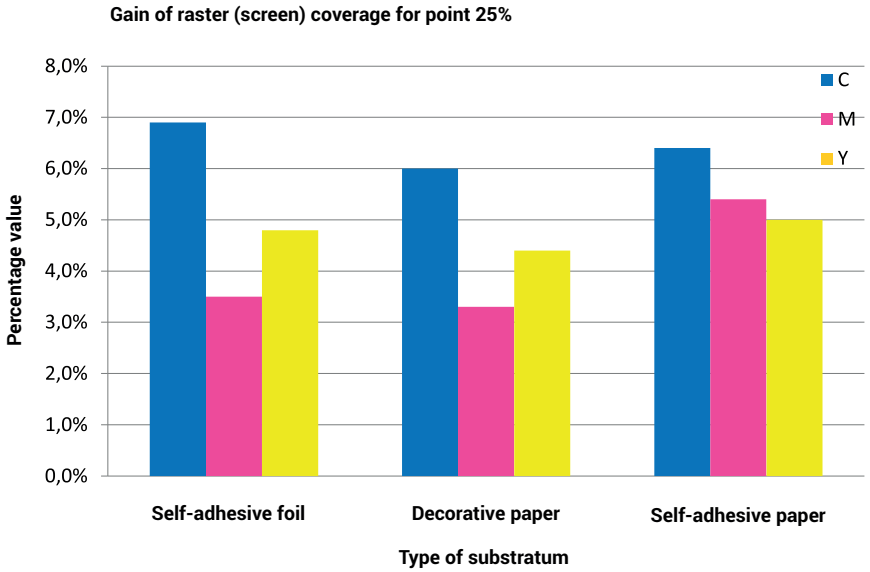

FIG.3. TONE VALUE INCREASE FOR POINT 25%

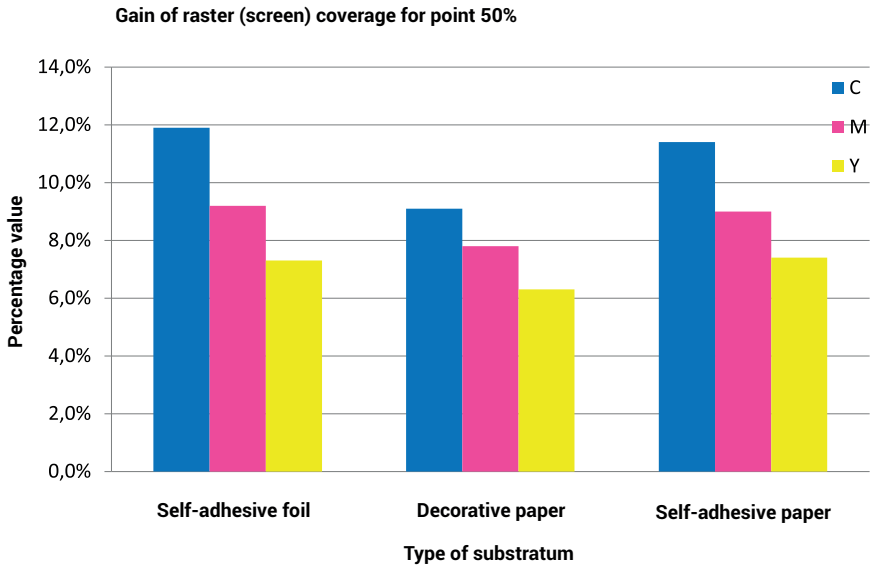

FIG. 4 TONE VALUE INCREASE FOR POINT 50%

differing significantly from the normative ones what results in unsatisfactory span of colors on the background of the remaining examined materials.

INCREASE OF TONAL VALUE

Within the frames of the experiment, there were also presented percentage levels of the tonal value gain on all prints. The measurements were performed for 10%, 25%, 50%, 75% and for 100% values of coverage of control fields. The results are illustrated by the diagrams (Fig.3-50).

On the grounds of the table and the presented results, we may state that the greatest gains of tonal value were recorded for Cyan whereas the lowest ones were found for Yellow. The values obtained for raster field with coverage of 25% for which the smallest gain was recorded for Magenta color are the exception. The greatest gains for Cyan result mainly from the stronger contrast and ink properties while the lowest values for Yellow are the consequence of small contrast. The exception of Magenta color in the case of 25-% coverage is typical of the low raster values where the subtle differences

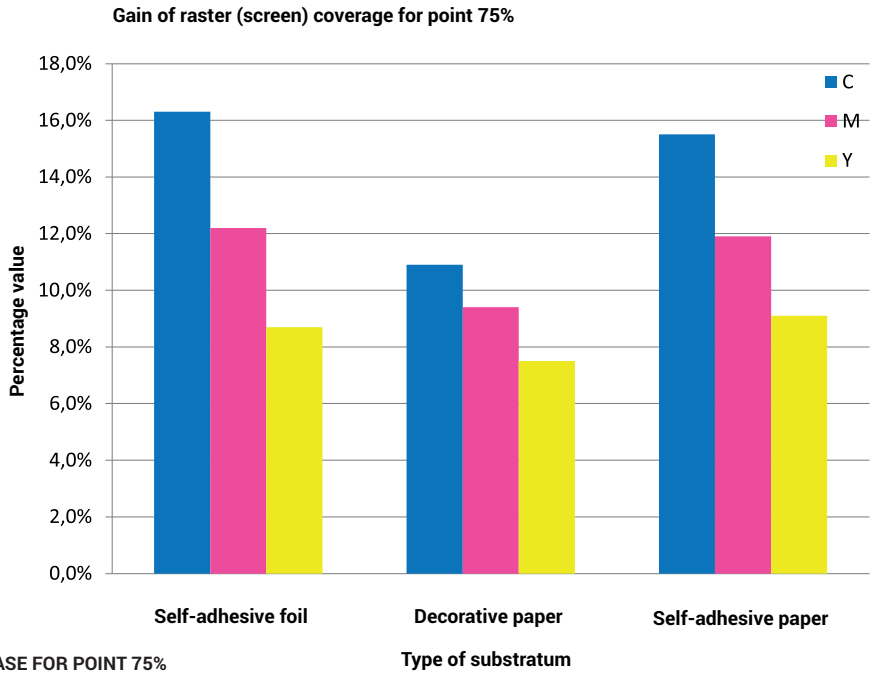

FIG. 5 TONE VALUE INCREASE FOR POINT 75%

in behavior of the single raster points and ink properties are decisive.

SUMMING UP AND ANALYSIS OF THE RESULTS

The aim of the conducted studies was to evaluate the impact of the printing substratum on the quality of the labels, produced by the digital inkjet printing in hybrid machine. The analysis covered three types of label materials: self-adhesive coated paper, self-adhesive decorative paper with texturized surface and self-adhesive polypropylene-based foil.

The results of the experiments have revealed a significant effect of the substratum properties on the quality parameters of the prints. The most advantageous results were obtained for self--adhesive foil and self-adhesive coated paper which were characterized by similar values of relative contrast, wide area of reproducible colors and high conformity with the requirements of ISO 12647. Especially, the adhesive foil ensured the greatest color gamut what is an evidence of very good possibilities of colors' reproduction.

Somewhat weaker results were obtained for decorative paper with the texturized surface. The mentioned material was characterized by a lower relative contrast, smaller area of reproducible colors and higher deviations from reference values, as specified in ISO standard. The discussed limitations result, first of all, from the uneven structure of the surface which affects the method of application and preservation of ink,

The analysis of the tonal value gain showed that the highest values were recorded for Cyan whereas the lowest ones were found for Yellow. The observed differences were connected with the optical properties of the particular inks as well as with the characteristics of the examined substratum.

The conducted studies have confirmed that the appropriate choice of label material has a crucial meaning for obtaining the high quality of digital prints. The self-adhesive foil and coated paper occurred to be the most favourable substrata in respect of quality parameters whereas the decorative paper, in spite of its high esthetic values, is connected with certain limitations in respect of image and color reproduction. The results of the studies may become practical guidelines for the choice of substrata for production of the labels, printed by the inkjet technology.

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USING ADAPTIVE NEURO-FUZZY INFERENCE SYSTEMS TO PREDICT ADHESION CHARACTERISTICS OF FLEXOGRAPHIC INK TO ALUMINUM FOIL

WYKORZYSTANIE ADAPTACYJNEGO SYSTEMU WNIOSKOWANIA NEURO-ROZMYTEGO DO PRZEWIDYWANIA ADHEZJI FARBY FLEKSOGRAFICZNEJ DO FOLII ALUMINIOWEJ

ABSTRACT: The effect of corona discharge treatment of aluminium foil surfaces, alongside the type and thickness of the roller-applied primer layer, on ink layer adhesion in flexographic printing for food packaging production has been investigated. An adaptive neuro-fuzzy inference system (ANFIS) was developed to predict ink-to-foil adhesion based on a combination of technological parameters.
Experimental studies were conducted utilising two surface treatment options (untreated and corona-treated), two types of roller-applied primers (acrylic and polyurethane), and three levels of wet primer layer thickness. Adhesion quality was evaluated in accordance with the international standard ASTM D3359 (Cross-cut tape test), while surface wettability was assessed by measuring the contact angle in accordance with ASTM D5946. It was established that the dependence of adhesion on primer layer thickness is nonlinear and extreme, peaking in the range of 2.3–2.6 µm. This is driven by the opposing effects of two factors: the improvement of coating continuity as thickness increases, and the rise in internal cohesive stresses coupled with slower drying times at excessive layer thicknesses.
The developed ANFIS model (R2=0.9841) provides higher accuracy in adhesion prediction compared to multiple linear regression (R2=0.7834). This is attributed to the fuzzy model's capability to correctly replicate the non-monotonic dependence of adhesion on layer thickness, which is unattainable using linear methods. The maximum adhesion is achieved through a combination of corona treatment and an acrylic primer with a layer thickness of 2.5 µm. The developed model can be utilised to optimise the technological parameters of roller primer application in flexographic printing on metallised substrates within the packaging industry.
Key words: flexographic printing, ink adhesion, aluminium foil, corona treatment, primer, ANFIS, neuro-fuzzy system, food packaging

STRESZCZENIE: W artykule przedstawiono badania wpływu obróbki powierzchni folii aluminiowej wyładowaniami koronowymi, a także rodzaju i grubości warstwy primieru, na przyczepność warstwy farby w druku fleksograficznym przy produkcji opakowań spożywczych. Na podstawie kombinacji parametrów technologicznych opracowano adaptacyjny system wnioskowania neuro-rozmytego (ANFIS) do przewidywania przyczepności farby do folii. Badania eksperymentalne przeprowadzone nporównianiu dwóch wariantów obróbki powierzchni (nieobrobionej i poddanej obróbce koronowej), dwóch rodzajów prajmierów (akrylowych i poliuretanowych) oraz trzech poziomów grubości warstwy zadrukowanej. Jakość przyczepności oceniano zgodnie z międzynarodową normą ASTM D3359 (test taśmy tnącej), natomiast zwilżalność powierzchni oceniano poprzez pomiar kąta zwilżania zgodnie z normą ASTM D5946. Stwierdzono, że zależność przyczepności od grubości warstwy primeru (podkładu) jest nieliniowa i ekstremalna, osiągając szczyt w zakresie 2,3–2,6 µm.
Opracowany model ANFIS (R2 = 0,9841) zapewnia wyższą dokładność prognozowania adhezji w porównaniu z wielokrotną regresją liniową (R2 = 0,7834). Wynika to ze zdolności modelu rozmytego do poprawnego odwzorowania niemonotonicznej zależności adhezji od grubości warstwy, co jest nieosiągalne metodami liniowymi. Maksymalną adhezję uzyskuje się poprzez połączenie obróbki koronowej z primerem akrylowym o grubości warstwy 2,5 µm. Opracowany model może być wykorzystany do optymalizacji parametrów technologicznych aplikacji primeru w druku fleksograficznym na podłożach metalizowanych w przemyśle opakowaniowym.
Słowa kluczowe: druk fleksograficzny, przyczepność farby, folia aluminiowa, obróbka koronowa, primer, ANFIS, system neuro-fuzzy, opakowania spożywcze

1. INTRODUCTION

Flexographic printing on aluminium foil is one of the most widespread methods of producing food packaging, providing high barrier performance, aesthetic appeal and the ability to reproduce complex graphic elements. Aluminium foil is characterised by excellent protective properties against light, oxygen, moisture and mechanical damage, which makes it an indispensable material for the packaging of food products, pharmaceuticals and cosmetics.

One of the key technological challenges in flexographic printing on metallised substrates is ensuring sufficient adhesion of the ink film to the foil surface. The low natural adhesion is caused by the high surface energy of the metal, the absence of porosity, and the smoothness of the surface. Insufficient adhesion leads to ink delamination during mechanical processing, transportation or the use of the packaging, which critically affects the quality of the printed product and the safety of the packaged goods.

Among the traditional approaches to improving adhesion, corona discharge surface treatment of the foil is one of the most technologically and economically acceptable solutions for industrial implementation, owing to its moderate energy consumption and ease of integration into the printing line. At the same time, the quality of the intermediate adhesive layer is largely determined by the type and thickness of the primer, as well as by its application method. Roller application of the primer is widely used in industrial practice because it allows precise control of layer thickness and provides high process productivity; however, its combination with different primer types and corona surface treatment has not yet been studied systematically [1-3].

1.1. ANALYSIS OF LITERATURE DATA AND PROBLEM STATEMENT

The study of the adhesive properties of printed coatings on foil substrates attracts considerable attention from researchers in the field of packaging technologies. Mandal and Bandyopadhyay [4] carried out a series of studies on the water resistance and light fastness of gravure prints on blister foil, applying artificial neural network methods to predict print degradation over time. Their work showed that neural-network models provide high prediction accuracy, significantly exceeding that of regression models.

Studies of the mechanisms of coating adhesion to metal substrates demonstrate the critical role of the surface energy and roughness of the substrate. Corona treatment generates active functional groups on the surface that promote chemical interaction between the ink (through the intermediate primer layer) and the foil. The effectiveness of the treatment depends substantially on the type of primer used and its application method.

The use of primers as an intermediate adhesive layer between the foil and the ink is common practice in packaging production. Acrylic primers are characterised by fast drying and good compatibility with water-based inks, while polyurethane primers offer high flexibility and resistance to mechanical stress. Unlike spray application, roller application provides a more uniform and controlled layer thickness, which is particularly important for thin primer coatings (2-3 μm); however, a systematic study of the effect of the combination of corona treatment with the type of roller-applied primer on adhesion in flexographic printing on aluminium foil has not been sufficiently conducted [5-7].

Traditional methods of adhesion modelling are based on empirical regression equations or simple feed-forward neural networks. Such approaches have limitations in reproducing complex non-linear dependencies and in incorporating expert knowledge of the technological process. Adaptive neuro-fuzzy inference systems (ANFIS) combine the advantages of neural networks (the capacity to learn) with those of fuzzy logic (the ability to incorporate expert knowledge), which makes them a promising tool for modelling complex technological processes [8-12].

Despite the existence of individual studies on coating adhesion and the application of intelligent systems in printing, no comprehensive approach has been identified in the available literature for predicting ink-film adhesion in flexographic printing on aluminium foil combining corona surface treatment and roller application of primers of varying thickness using ANFIS.

1.2. AIM AND OBJECTIVES OF THE STUDY

This work aims to apply an adaptive neuro-fuzzy inference system to predict ink-film adhesion in flexographic printing on

aluminium foil, in order to optimise the technological parameters of food-packaging production.

To achieve this aim, experimental studies were carried out on the effect of corona treatment of the foil surface and two primer types (acrylic and polyurethane), applied in layers of varying thickness by the roller method, on ink-film adhesion. Based on the data obtained, a set of adhesion-quality indicators was determined, including abrasion resistance, the contact angle, and the results of the cross-cut tape test.

The next stage involved the development of an intelligent prediction system. An adaptive neuro-fuzzy inference system (ANFIS) structure was developed for adhesion prediction, which was subsequently trained and validated on the collected experimental data. The final step was a comparative analysis of the prediction accuracy of the ANFIS model against a conventional regression model and a standard neural network, making it possible to determine the optimal technological parameters for ensuring maximum adhesion within the studied range.

2. MATERIALS AND METHODS

The study used 20 µm thick aluminium foil of the Alufoil 1235 brand from Aluflexpack, intended for the production of flexible food packaging. For flexographic printing, water-based flexographic inks Flint Group Hydrokett ZEN (viscosity 18-22 s according to the Ford cup #4 viscometer at 25°C) were used.

Primers (for roller application):

– Acrylic DuPont Tyvek Primer (water-based, drying time 5-7 s)
– Polyurethane two-component 3M Adhesion Promoter 94 (solid content 22%, drying time at 50°C — 8–10 s).

The control group within each type of primer consisted of samples without pre-treatment of the foil surface (i.e., without corona treatment), which allowed for isolating the effect of corona treatment from the effect of the primer type.

Corona treatment was carried out on an Enercon Corona Treater with a discharge power of 3.5 kW/m² at a material feed rate of 50 m/min. The treatment level was controlled with test inks (38 mN/m). The control group of samples was not subjected to surface pretreatment.

Primers were applied by the roller method, which is standardly used in flexible packaging production. The wet primer layer thickness was adjusted by selecting an anilox metering roll with a different cell volume (Table 1).

After application, the primer was dried in a tunnel dryer at 50°C for 8-10 s. For the control samples (without primer), application and drying were not carried out.

Printing was carried out on a laboratory flexographic printing press IGT F1, at a web speed of 80 m/min and a printing pressure of 60 N/cm. The application of the ink film in the printing unit was provided by means of an anilox roll with a line screen of 120 lines/cm and a specific cell volume of 8 cm^3/m^2, while the image transfer itself was performed from photopolymer printing plates 1.7 mm thick. Fixing and setting of the resulting imprint were achieved by convective hot-air drying at a stable temperature of 60°C.

Cross-cut Tape Test (ASTM D3359) [13]: A 2×2 mm grid incision was made on the printed surface (10×10 grid incisions). A standard adhesive tape was applied, pressed and peeled off at an angle of 180°. The evaluation was carried out on a five-point scale (0 - complete peeling, 5 - no peeling).

Contact angle (ASTM D5946) [14]: measurement of the contact angle of distilled water on the foil surface after treatment was carried out by the sessile drop method on a goniometer. The drop volume was 5 µl, and the measurement time was 5 seconds after application. This indicator serves as an auxiliary input to the ANFIS model, reflecting the effectiveness of the surface treatment.

The study was carried out according to a full factorial design 2×2×3 with four replications (Table 2).

Total number of combinations: 2×2×3 = 12. Number of replications: 4. Total sample size: 48 experimental points. Samples without primer (control) were also included in the design under factor B (as a third level, B_0 "no primer"), which made it possible to quantitatively assess the effect of the primer on adhesion.

The adaptive neuro-fuzzy inference system (ANFIS) is based on a zero-order Sugeno model and consists of five stages: fuzzification — rule application — normalisation — defuzzification — aggregated output.

TABLE 1. ROLLER-APPLICATION PARAMETERS OF THE PRIMER AT DIFFERENT LEVELS OF FACTOR C

Level of factor C	Wet layer thickness (μm)	Anilox roll (cell volume, cm^3/m^2)	Roll line screen (lines/cm)	Application speed (m/min)
C_1 (low)	1.5	4	180	50
C_2 (medium)	2.5	8	140	50
C_3 (high)	3.5	12	110	50

TABLE 2. FACTORS AND LEVELS OF THE FULL 2×2×3 FACTORIAL DESIGN

Factor	Factor description	Levels	Notation
A	Surface treatment	Untreated / Corona	A_1 / A_2
B	Primer type	Acrylic / Polyurethane	B_1 / B_2
C	Wet layer thickness at roller application	1.5 / 2.5 / 3.5 μm	C_1 / C_2 / C_3

TABLE 3. RESULTS OF THE FACTORIAL EXPERIMENT: MEAN ADHESION VALUES (SCORE, ASTM D3359) ± STANDARD DEVIATION (N = 4)

Surface treatment (A)	Primer type (B)	Layer thickness C (μm) → Adhesion (score)		
		C_1 = 1.5 μm	C_2 = 2.5 μm	C_3 = 3.5 μm
Untreated (A_1)	No primer (B_0)	2.5 ± 0.1	—	—
	Acrylic (B_1)	2.9 ± 0.2	3.4 ± 0.1	3.0 ± 0.2
	PU (B_2)	2.7 ± 0.2	3.1 ± 0.2	2.8 ± 0.3
Corona (A_2)	No primer (B_0)	3.5 ± 0.1	—	—
	Acrylic (B_1)	3.8 ± 0.2	4.5 ± 0.1	4.0 ± 0.2
	PU (B_2)	3.5 ± 0.2	4.2 ± 0.1	3.7 ± 0.2

Input variables of the model:

x_1 surface-treatment type
(binary scale: 0 — untreated, 2 — corona-treated).

x_2 primer type, roller application
(binary scale: 0 — acrylic, 2 — polyurethane).

x_3 wet primer layer thickness (μm, continuous: 0; 1.5; 2.5; 3.5).

Output variable of the model: y — ink-film adhesion (score on the ASTM D3359 scale, from 0 to 5).

Number of membership functions for each variable: 2 for x_1 (binary), 3 for x_2, and 3 for x_3 ("thin", "optimal", "excessive"). The type of membership function is triangular (trimf) for x_1 and x_2, and Gaussian (gaussmf) for x_3, which ensures a smooth representation of the non-linearity with respect to layer thickness. Total number of fuzzy rules: 2×3×3 = 18 Sugeno rules.

ANFIS training was carried out by a hybrid method: the least-squares estimation (LSE) method for tuning the consequent parameters, and the back-propagation method for tuning the antecedent parameters (the centres and widths of the membership functions).

Data split: 70% (34 points) — training set, 30% (14 points) — test set. Stratified sampling ensured uniform representation of all factor combinations. The stopping criterion was the minimisation of the RMSE on the test set, or reaching 200 epochs.

Multiple linear regression (MLR) with the same input variables was used for comparative analysis. The choice of MLR as a comparator (rather than an MLP neural network) is justified by the principal aim of the article — to demonstrate the fundamental inability of an adequate linear model to represent the non-linear dependence on primer layer thickness.

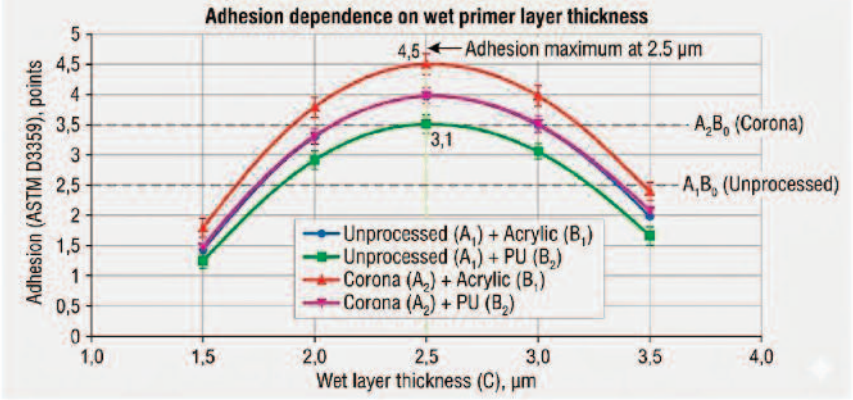

FIG. 1. NON-LINEAR DEPENDENCE OF ADHESION ON PRIMER LAYER THICKNESS FOR DIFFERENT COMBINATIONS OF SURFACE TREATMENT AND PRIMER TYPE

3. RESULTS

The results of the full 2×2×3 factorial experiment (averaged over 4 replications) are given in Table 3. The data reveal a key pattern: a non-linear dependence of adhesion on primer layer thickness, with a clearly defined maximum at 2.5 µm for both primer types (Table 3).

Analysis of the data in Table 3 confirms a non-linear dependence of adhesion on wet primer layer thickness, with a maximum at 2.5 µm for all combinations of factors A and B. As the thickness increases from 1.5 to 2.5 µm, adhesion increases by 15–18% owing to more complete surface coverage and the formation of a continuous barrier layer. With a further increase to 3.5 µm, adhesion decreases by 8–12% relative to the maximum, which is explained by the development of internal cohesive stresses in an excessively thick primer layer and by slower drying (Fig. 1).

This non-linearity is fundamentally important for the choice of modelling method: linear regression approximates it with a straight line, failing to reproduce the maximum, which leads to a systematic prediction error.

Corona treatment reduces the contact angle from 91.5° to 63.2°, indicating an increase in surface energy and wettability. This confirms the effectiveness of corona treatment for activating the aluminium-foil surface and explains the higher adhesion values for combinations with factor A_2 compared with A_1.

The trained ANFIS model contains 18 Sugeno fuzzy rules. The training curve shows rapid convergence: the minimum RMSE value on the test set is reached at the 94th epoch (Fig. 2).

Examples of the trained fuzzy rules (zero-order Sugeno consequents):

Rule 7: IF (x_1 = Corona) AND (x_2 = Acrylic) AND (x_3 = Optimal) THEN y = 4.48

Rule 1: IF (x_1 = Untreated) AND (x_2 = No_primer) AND (x_3 = Thin) THEN y = 2.50

A comparison of the prediction quality of ANFIS and MLR is given in Table 4. The substantial difference in R^2 (0.9841 versus 0.7834)

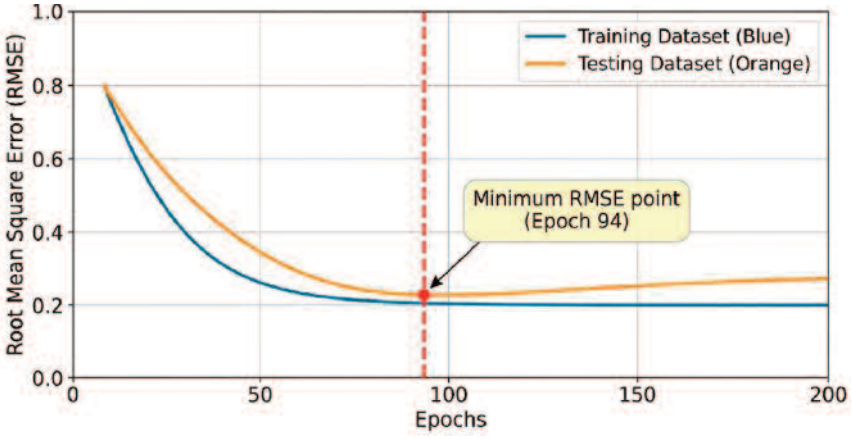

FIG. 2. ANFIS MODEL TRAINING CURVE: RMSE AS A FUNCTION OF THE NUMBER OF EPOCHS

TABLE 4. ADHESION-PREDICTION QUALITY METRICS

Model	R^2	RMSE	MAE	MAPE (%)
MLR (linear regression)	0.7834	0.5241	0.4180	13.62
ANFIS	0.9841	0.1956	0.1520	4.21

is a direct consequence of the non-linear character of the dependence on factor C: MLR is unable to reproduce the adhesion maximum at 2.5 μm, whereas ANFIS, with its Gaussian membership functions, adequately approximates this effect.

ANFIS shows an R^2 value that is 20.5 percentage points higher than that of MLR. The RMSE of ANFIS is 2.68 times lower. This advantage is explained by the fundamental inability of the linear model to reproduce non-linear dependencies with a maximum.

The ANFIS response surface for the combination of A_2 (corona treatment) and B_1 (acrylic primer), as a function of layer thickness C, shows a clear parabolic profile with a maximum at C_2 = 2.5 μm (Fig. 3). Analysis of all 18 rules confirms that the optimal combination of parameters — $A_2B_1C_2$ — provides an adhesion score of 4.5.

Sensitivity analysis by the partial-dependence method revealed the relative contribution of each factor to the variation in predicted adhesion: factor A (surface treatment) — 38.2%; factor B (primer type) — 33.6%; factor C (layer thickness) — 28.2% (Fig. 4).

All three factors have a significant effect on adhesion, which confirms the appropriateness of including primer layer thickness as a quantitative factor in the study design. The relatively even distribution of contributions indicates the absence of a single dominant factor, which underlines the need for a systematic approach to optimising the technological process.

4. DISCUSSION OF RESULTS

The established parabolic dependence of adhesion on wet primer layer thickness (with a maximum at 2.5 μm) is physically well-founded and characteristic of adhesive systems involving polymeric coatings.

On the rising branch (1.5 → 2.5 μm), the increase in adhesion is explained by an improved completeness of surface wetting and coverage: at the minimum thickness of 1.5 μm, individual areas of the surface remain uncovered by the primer, which reduces the effective area of adhesive contact. At 2.5 μm, continuous, uniform coverage is achieved, and a complete barrier layer forms between the foil and the ink, providing maximum adhesion.

On the falling branch (2.5 → 3.5 μm), the decrease in adhesion is caused by several mechanisms:

(1) an increase in internal cohesive stresses in the excessively thick polymeric primer layer as it shrinks during drying;

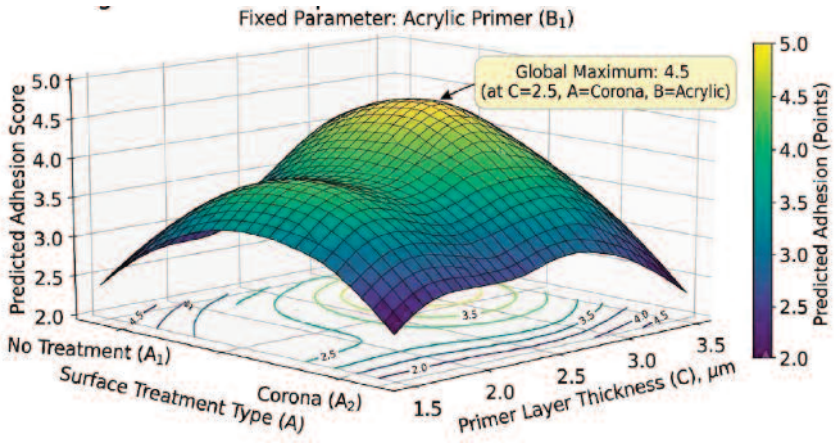

FIG. 3. ANFIS RESPONSE SURFACE: PREDICTED ADHESION AS A FUNCTION OF PRIMER LAYER THICKNESS AND SURFACE-TREATMENT TYPE

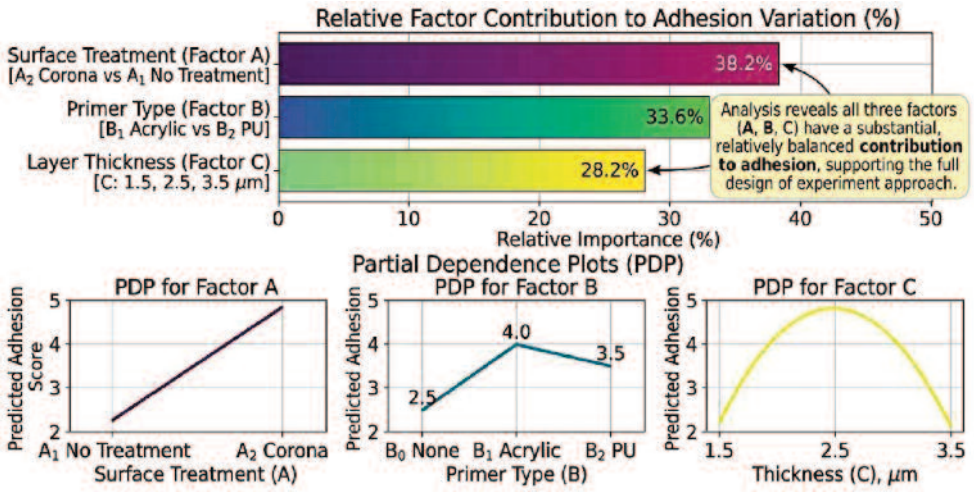

FIG. 4. SENSITIVITY ANALYSIS: RELATIVE CONTRIBUTION OF THE FACTORS TO PREDICTED ADHESION VARIATION

(2) incomplete drying of the inner layers under rapid calendaring, leading to the migration of the solvent/binder to the ink-primer interface;

(3) a reduction in intermolecular contact between the outer layer of the primer and the ink components due to a change in surface morphology.

The acrylic primer provides a 6–7% higher adhesion than the polyurethane primer across all factor combinations at equal layer thickness. This is explained by the higher compatibility of the polar acrylate groups with the water-based Hydrokett ZEN flexographic inks and the faster drying of the acrylic primer (5–7 s versus 8–10 s for PU), which minimises diffusional mixing at the layer interface.

The polyurethane primer, despite somewhat lower adhesion values compared with the acrylic primer, provides higher coating elasticity, which is an advantage for packaging subjected to deformation (heat-sealing, wrapping). The choice between acrylic and PU primers in industrial production should take into account not only adhesion but also the mechanical requirements of the finished product.

Corona treatment increases adhesion by an average of 28-32% relative to untreated foil under the same primer parameters. The physical mechanism consists of the generation of active functional groups on the surface of the aluminium oxide, which increases the surface energy (a reduction in the contact angle from 91.5° to 63.2°) and the chemical affinity for the polar groups of the primers.

From a practical standpoint, corona treatment is the optimal activation method for industrial flexographic production, owing to the possibility of continuous integration into the printing line, its low energy consumption, and the stability of results in mass production.

The key methodological value of this study lies in demonstrating the fundamental advantages of ANFIS over linear regression for modelling adhesive systems with non-linear dependencies. MLR, by approximating the dependence on layer thickness with a straight line, systematically overestimates adhesion at thin layers (1.5 μm) and underestimates it at the optimal thickness (2.5 μm), resulting in a MAPE of 13.62% — an unacceptable level of error for industrial application.

ANFIS, owing to the Gaussian membership functions for the variable x_3 (layer thickness), accurately reproduces the parabolic adhesion profile, with a MAPE of 4.21%. At the same time, the system generates interpretable fuzzy rules, allowing technologists to understand the prediction logic and to trust the system's recommendations. This is a fundamental advantage of ANFIS over MLP-type neural networks.

The developed ANFIS model can be used under production conditions for:

(1) the rapid determination of the optimal anilox roll when the primer or substrate type is changed;

(2) real-time control of adhesion quality based on contact-angle measurements and application parameters;

(3) the accelerated screening of new primer types through a minimal number of verification experiments.

Limitations of the study:

(1) only water-based flexographic inks were used — for UV-curable inks, the dependencies may differ;

(2) the long-term stability of adhesion under elevated humidity and temperature cycling was not investigated;

(3) the layer-thickness range was limited to 1.5–3.5 μm, which is characteristic of anilox metering in roller-applied flexographic printing.

5. CONCLUSIONS

1. The implemented full 2×2×3 factorial design (48 points), with the factors "surface treatment", "primer type" and "wet primer layer thickness in roller application", provided a sufficient volume and variation of data for training and validating the ANFIS model with non-linear dependencies.
2. A non-linear, parabolic dependence of adhesion on wet primer layer thickness was established, with a maximum at 2.5 μm: an increase from 1.5 to 2.5 μm provides an adhesion gain of 15–18% (complete surface coverage), while a further increase to 3.5 μm reduces adhesion by 8-12% owing to internal cohesive stresses in the excessively thick layer.
3. Corona treatment increases adhesion by an average of 28-32% relative to the untreated surface, reducing the contact angle from 91.5° to 63.2°. The acrylic primer provides 6-7% higher adhesion than the polyurethane primer for the selected water-based flexographic inks.
4. The developed ANFIS model with 18 Sugeno fuzzy rules shows R^2 = 0.9841 and an RMSE of 0.1956 score points, which is 20.5 percentage points more accurate than multiple linear regression (R^2 = 0.7834). The advantage of ANFIS is a direct consequence of the non-linear character of the dependence on primer layer thickness.
5. The optimal technological parameters for flexographic printing on aluminium foil were determined: corona surface treatment + acrylic primer + wet layer thickness of 2.5 μm (anilox roll 8 cm^3/m^2, 140 lines/cm) at an application speed of 60 m/min and drying at 50 °C. This combination provides an adhesion score of 4.5 according to ASTM D3359.
6. Sensitivity analysis of the ANFIS model showed a relatively even contribution of all three factors to the variation in adhesion (A: 38.2%, B: 33.6%, C: 28.2%), confirming the need for a systematic consideration of surface treatment, primer type and layer thickness when optimising the flexographic printing process on metallised substrates.

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INTERPACK 2026 SENDS A GLOBAL SIGNAL FOR THE PACKAGING INDUSTRY

interpack 2026 made the energy of an entire industry truly tangible. Once again, it became the global meeting place for the processing and packaging industry and impressively demonstrated how concrete transformation is already being implemented in technology, materials and processes.

interpack 2026 sent a clear signal: the packaging industry is more closely connected, more innovative and more dialogue-oriented than ever before. This momentum was immediately visible in the exhibition halls. High visitor traffic, intensive discussions and a consistent international presence shaped the atmosphere. Everywhere, it was possible to experience the determination with which companies are working on solutions for the future. Ideas were discussed, tested and decisions were made. The entire value chain was presented in live.

From 7 to 13 May, 2,804 exhibitors from 65 countries and trade visitors from 161 countries came together in Düsseldorf on the fully booked exhibition grounds. Of all visitors, 75 percent came from outside Germany, including 28 percent from outside Europe. Around 100 additional companies were represented at components, the supplier trade fair held in parallel. This made interpack 2026 the largest edition in its history in terms of exhibitors, underlining what was clearly felt in the halls: this was an event with exceptional impact.

That was a top interpack. Busy halls, intensive exchange and concrete projects showed the strength of this global community. interpack is the most important meeting place for the industry worldwide, and this edition impressively confirmed that – said **Thomas Dohse, Director of interpack**, at the close of the trade fair.

For seven days, concrete solutions and partnerships took centre stage. Many discussions led to projects and investment decisions. The trade fair thus confirmed its role as the leading platform for the global processing and packaging industry – with strong visitor attendance, particularly from the food and pharmaceutical industries, as well as a high quality and density of leading and innovative suppliers.

MARKET GROWTH – INDUSTRY UNDER PRESSURE

interpack 2026 took place at a time when the industry is undergoing transformation. Demand for packaged products continues to rise, but requirements for materials, production systems and supply structures are changing. A key focus at the trade fair was the European Packaging and Packaging Waste Regulation (PPWR), which marks a turning point for the industry in many respects.

interpack made one thing clear: companies are not responding in isolation, but systemically. Exhibitors presented solutions in which materials, machines and processes are increasingly considered together and coordinated with one another. In this way, interpack confirms its role as an economic driver for the industry: this is where projects are initiated, investments prepared and economic momentum generated.

SYSTEMS, MATERIALS, SKILLS

Automation, data-based applications and flexible plant concepts have arrived in industrial practice and were presented at interpack as concrete applications of smart manufacturing. In the field of materials, the focus was on innovative solutions that work under real-world conditions and meet regulatory requirements. Future skills became tangible wherever connected and data-driven systems require new competencies in production. Personal proximity, shared experiences and open dialogue gave interpack a special intensity.

SPECIALS PROVIDE ADDITIONAL IMPETUS

interpack also set important accents beyond the exhibition stands. The enhanced specials complemented the trade fair activities and brought in additional perspectives. The interpack Spotlight Forum, SAVE FOOD Expert Talks, Women in Packaging, the Start-up Zone and Young Talents Day showed how broadly the industry's transformation is being discussed – from technology and sustainability to diversity, start-up culture and the promotion of young talent, as well as qualification and future skills.

What remains is more than a successful trade fair. It is a clear signal: the industry faces major challenges and is meeting them with innovative strength, cooperation and the will to actively shape the future. Added to this is a special combination of international density, technical depth and a palpable spirit of new beginnings that characterised this interpack.

The next interpack will take place in 2029. The date will be announced.

FOT. CONSTANZE TILLMANN

PLASTPOL 2026: LIVE MACHINERY DEMONSTRATIONS AND MULTI-MILLION CONTRACTS IN KIELCE

Fifteen thousand visitors from Europe, Asia and Africa, 660 exhibitors from 36 countries, hundreds of machines operating live, contracts worth millions, and the celebration of the event's 30th anniversary – the International Fair of Plastics and Rubber Processing PLASTPOL further strengthened its position as one of Europe's leading industry events. For four days, Targi Kielce became one of the world's most important meeting places for the plastics processing industry.

PLASTPOL showcased the latest global technologies and raw materials, while Targi Kielce once again served as a venue for industry meetings, business negotiations, contract signings and the establishment of new commercial partnerships. Throughout the exhibition halls, injection moulding machines, extrusion lines, industrial robots, fully automated production systems and recycling technologies operated live. Demonstrations included the production of insulin pen components, medical autoinjector parts, lunch boxes, industrial components, and products manufactured from recycled and natural materials.

Companies from the medical, food, packaging, logistics, household appliance and automotive sectors invested in modern machinery, automation and energy-efficient manufacturing solutions.

Customers are increasingly looking for solutions that enable predictable production management, reduce scrap rates and optimize energy and resource consumption – said **Adam Marciniak from Engel**, whose company secured machine orders during the exhibition.

During the four-day event, dozens of machines and complete plastics processing production lines were sold. Companies

including BOLE, Plastline, Plastigo, Proplastica, Sumitomo (SHI) Demag, Bagsik, LS Mtron, Mapro and Muehsam Industrial Solutions reported signed contracts and advanced commercial negotiations. Although exhibitors acknowledged the slowdown in the European plastics market, there was a prevailing sense of cautious optimism, with companies emphasizing the need for continued investment in efficiency, recycling and automation.

30 YEARS OF PLASTPOL – A CELEBRATION OF THE INDUSTRY

The 30th edition of PLASTPOL had a special anniversary character. During the Platinum Plast Gala, companies that have helped shape both the exhibition and the plastics processing industry since its earliest editions were honored.

The "Architect of Success" awards were presented to Muehsam Jan Krzysztof i Wspólnicy, Dopak, Engel, Wittmann Battenfeld, Danje Polymer, Polimarky, A. Marciniak OT, Bagsik, Proplastica, Telko, Finke Colors, KGL, Elbi, P&F Wartacz, the Łukasiewicz Research Network – Institute of Polymer Materials, Sumitomo Demag, PlastLine, Asten Group, Mapro Polska, Hasco Hasenclever, Moretto S.p.A., Grupa Azoty, PlasticsEurope Polska Foundation, Enterio, the Polish Association of Plastics Processors, and Tworzywa Media.

A particularly memorable moment of the gala was the recognition of Kamil Perz, Director of PLASTPOL, who has been involved in developing the exhibition for all 30 years of its history. The Management Board of Targi Kielce presented him with a special Atlas statuette carrying the globe as a symbol of his commitment, energy and contribution to the development of one of Europe's most important plastics industry exhibitions.

GOLD MEDALS FOR INNOVATION

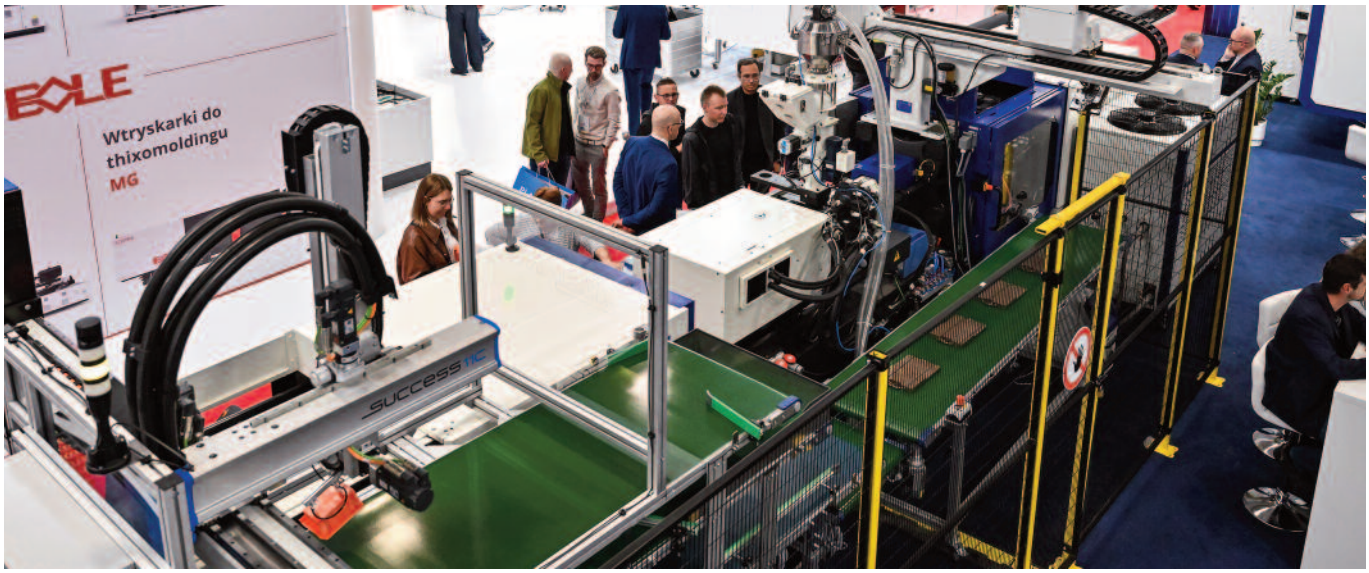
The gala also featured the presentation of the prestigious PLASTPOL Gold Medals for the most innovative products and technologies exhibited during the fair. The awards recognized solutions addressing the current needs of industry, particularly in automation, recycling, energy efficiency and artificial intelligence.

The winners included:

- XALOY EUROPE for the NeXtwin tungsten carbide conical barrel solution.
- KOLTEX PRS for the ERFOR XR8 extrusion line.
- BMB S.p.A. for the eKW20Pi/700 all-electric injection moulding machine.
- THERMOPLAY, part of the Spectrix Group, for its waste-free side injection moulding solution.
- DOPAK for industrial process support technologies.
- BOLE EUROPE TECHNOLOGY for its direct injection technology for long-fibre reinforced thermoplastic composites.

Polish companies receiving Gold Medals included:

- MUEHSAM Industrial Solutions for its hooding machine.



– PAWFORM for the E-DRIVE servo gearbox system.
– KGL for recyclable Menubox takeaway packaging manufactured from expanded polypropylene (XPP) film.

Honorable mentions were awarded to Plastoplan Polska, Mapro Polska, Ekochem, Ebs Ink Jet System Poland and MUEHSAM Industrial Solutions.

OMNIPLAST AWARDS FOR INDUSTRY EXPERTISE

During PLASTPOL, representatives of exhibiting companies were also recognized in the OMNIPLAST competition for their specialist knowledge and industry expertise. Organized jointly with the industry portal tworzywa.pl for the past fifteen years, the competition promotes professional competence within the plastics processing sector and has become one of the industry's most respected initiatives.

The final took place during the exhibition, with organizers highlighting the exceptionally high technical standard demonstrated by all participants.

This year's winner was Monika Zuber from Sierosławski Group, who received the prestigious OMNIPLAST trophy together with the main prize – a voucher worth PLN 8,000 for services at next year's PLASTPOL exhibition.

Second place was awarded to Tomasz Pyrek from DRP Group, who received a voucher worth PLN 6,000, while third place went to Justyna Przęczek from Polimer Projekt, who was awarded a voucher worth PLN 4,000.

CONFERENCES FOCUSED ON THE FUTURE OF THE INDUSTRY

Industry conferences, seminars and expert competitions formed an integral part of PLASTPOL 2026.

The European premiere of the Plastics Europe report Plastics in a Circular Economy – An Analysis of the Situation in Europe attracted significant attention from both industry professionals and the media. During the exhibition, the PlasticsEurope Polska Foundation also launched its Circular Plastics Compass Starter initiative.

The Plastech Info Technical Seminar, organized by the industry portal tworzywa.pl under the theme There Is No World Without Plastics, focused on current market challenges. Another conference, organized by eplastics.pl, addressed the Packaging and Packaging Waste Regulation (PPWR) and its implications for the European packaging industry.

A new addition to this year's programme was the international conference Italian Polymers, Compounds & Masterbatch Solutions – Expertise Driving Innovation in Automotive, organized jointly with Confindustria Polonia. Italian experts and companies presented advanced solutions for the automotive industry, including polymers, compounds, colour masterbatches and technologies designed to meet the evolving needs of Europe's automotive sector.

TARGI KIELCE – WHERE BUSINESS GETS DONE

Trade fairs remain the most human place to do effective business, said **Dr Andrzej Mochoń, President of the Management Board of Targi Kielce**. *Live machinery demonstrations reveal the full capabilities of the equipment. At every stand, professional visitors have direct access to sales specialists, technical experts and company executives, enabling them to obtain comprehensive technical information while simultaneously negotiating commercial terms.*

PLASTPOL 2027 TO DEBUT IN A NEW EXHIBITION HALL

We are already looking forward to welcoming the industry to the next edition of PLASTPOL, which will take place from 18 to 21 May 2027 and will be held in Targi Kielce's brand-new exhibition hall. The new facility will allow us to offer exhibitors even greater opportunities, said **Kamil Perz, PLASTPOL Project Director**.

The new hall, offering more than 15,500 square metres of exhibition space with a height of 15 metres, has been specifically designed for demanding industrial displays and heavy production lines. Exhibitors will be able to construct stands up to eight metres high.

Direct access through seven large gates for machinery deliveries will significantly improve logistics, while the floor load capacity of 100 kilonewtons per square metre will accommodate even the heaviest industrial machinery and large-scale technological installations.

Packaging Review

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ALL SCIENTIFIC ARTICLES ARE REVIEWED.

"PACKAGING REVIEW" REVIEWING PROCEDURE

"Packaging Review" quarterly magazine's reviewing procedure is multilevel in order to maintain high quality content and consists of the following steps:

- If Editor-in Chief decides that provided, scientific article fits the journal's scope, he appoints two Reviewers of recognized competence within the field of research, preferably with professor or postdoctoral degree. The reviewers are obliged to:
  - deliver an objective, independent opinion,
  - ensure that there is no conflict of interests – they should have no personal relationships or business relations with Authors,
  - keep any information regarding the content and opinion confidential.
- When the Reviewers are chosen, the Editor-in-Chief sends them a written offer with either a short description or an abstract of the article, defines the range of reviews and sets a deadline.
- If the Reviewers accept the offer, the Editorial Board provides them with a full version of the article and an obligatory peer review report.
- Reviewers' personal details are classified and they can be declassified only at the Author's request and with the reviewer's permission in case the review is negative or the article contains arguable elements. Once a year, the Editorial Board publishes in its journal the full list of the Reviewers cooperating with the journal.
- Once the review process is complete, the Reviewer delivers electronic version of the review by e-mail and the Editorial Board:
  - informs the Author that the review has been submitted to the journal (when the reviewer states that the article does not require corrections or it requires only minor editorial corrections),
  - forwards the review with critical comments to the Author, who is encouraged to make corrections suggested by the reviewer. If the Author disagrees with certain remarks, he/she is under obligation to prepare response letter substantiating his position.
  - sends the revised article to the Reviewer again, if the Reviewer finds it necessary.
- The Editorial Board makes the final decision about publishing the article based on analysis of the review and the revised version of the article that the Author has resubmitted.
- If one of the reviews is negative, the Editor-in-Chief makes decision about rejection of the article or invites an additional reviewer so as to get an extra opinion before making a decision. When both reviews are negative, the Editor-in-Chief rejects the article.
- The final version of the article is sent to the Author.
- Non-scientific articles do not need to be reviewed and they are accepted for publication by the Editor-in-Chief.

INFORMATION FOR THE AUTHORS

We kindly ask to submit to the editorial office author's application form available at www.packagingreview.eu with contact details, a title of the proposed article, number of pages, illustrations and tables as well as a brief abstract. After receiving information about the acceptance of the proposed article please submit the entire text prepared according to the editorial instructions as well as a complete declaration form. Submitted articles are subjected to editorial assessment and receive a formal editorial identification number used in further stages of the editorial process. Every submitted article is reviewed. Publication is possible after receiving positive reviews.

GUIDELINES FOR PREPARING THE ARTICLES

- Articles for publication in „Packaging Review" should have scientific and research character and focus on innovations, trends and challenges of the industry.
- Articles must be original, not previously published (if the article is a part of another work i.e. PhD thesis, habilitation etc. the information about that should be placed in the reference section).
- The article should involve a narrow topic but treated thoroughly without repeating general knowledge information included in the widely known literature.
- If the problem is extensive, it should be it split into few articles for separate publications.
- Articles should be of a clear and logical structure: the material should be divided into parts with titles reflecting its content. The conclusions should be clearly stated at the end of the paper.
- The article should be adequately supplemented with illustrations, photographs, tables etc. however, their number should be limited to absolute necessity.
- The title of the article should be given in Polish and English as well as the abstract and key words.
- The article should not exceed 10 pages (1 page – 1 800 characters).
- The article should include post and e-mail addresses of the author (s).
- The article should be electronically submitted in *doc or *docx format and additionally PDF format. Equations should be written in the editors, with a clear distinction between 0 and O. If the equations exceed the width of column (8 cm) they must be moved, otherwise use double width column (16 cm).
- The editorial staff does not rewrite the texts or prepare illustrations. Apart from *.doc, *.docx formats it is recommended to submit the source files of illustrations (in *.eps, *.jpg or *.tif format).
- Drawings and graphs must be clear and fit A4 size of the column.
- The text on the drawings cut to the size must be legible and not less than 2 mm.
- The authors are required to give at the end of the article a full list of sources used for the paper. The text must include citation references to the position of cited work in the bibliography. The bibliography prepared according to the references in the text must include: books – surname and first letter of the author's name, title, publisher, year and a place of publication (optionally page number), magazines – author's name and surname, title of the article, title of the magazine, number, year and optionally page numbers. The bibliography should present the current state of knowledge and take into account publications of world literature.
- The authors guarantee that the content of the paper and drawings are originally theirs (if not the source must be included). The authors by submitting the article transfer the ownership rights to the publisher for paper and electronic publication.
- The editorial staff will document all form of scientific misconduct, especially violations of the rules of ethics applicable in science.

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