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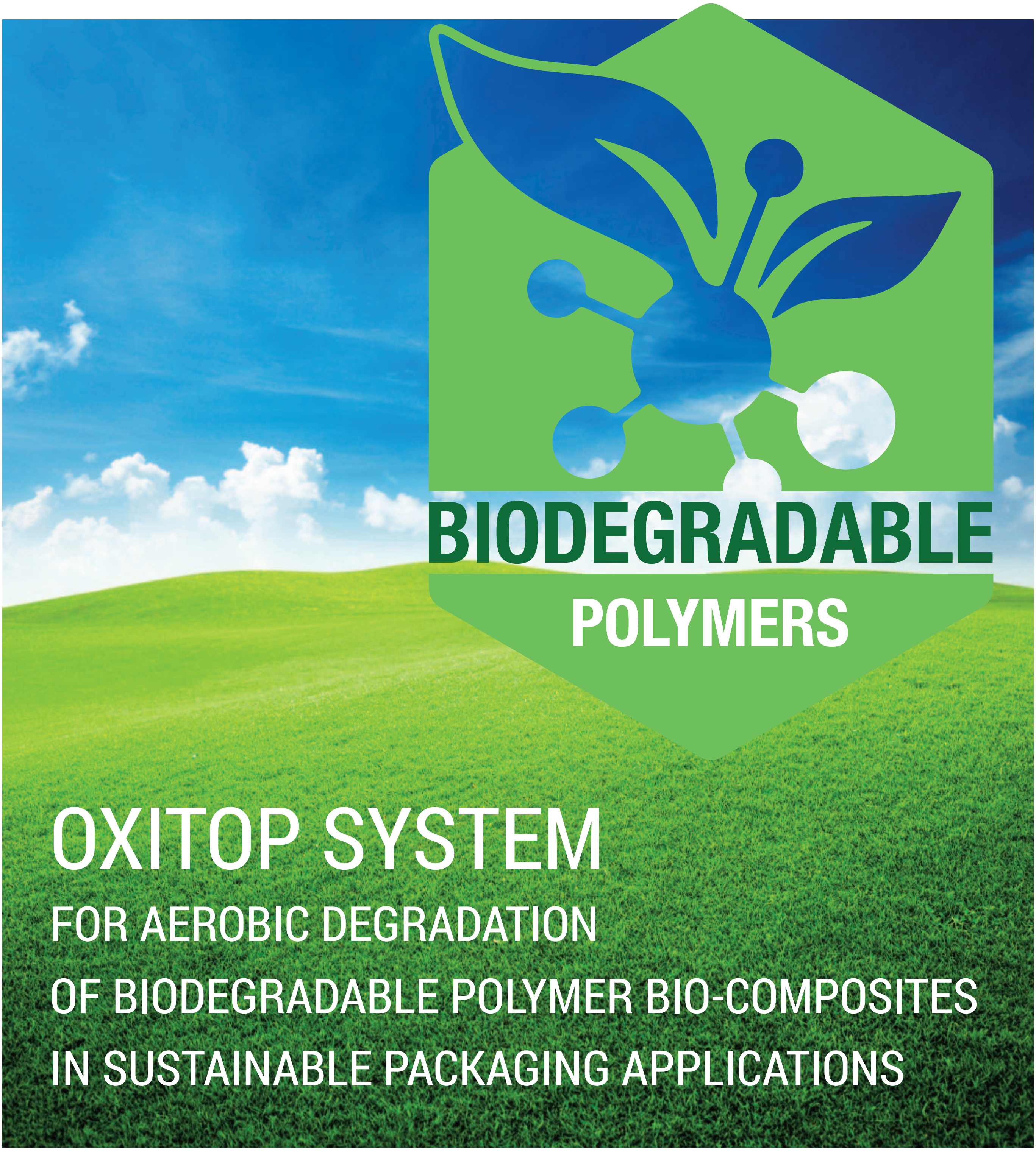


16
Safe
CONFERENCE
packaging
November 4-6th, 2026
ZAMEK TOPACZ
WROCŁAW
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Packaging Review

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Dear Readers!

The next edition of **"Safe Packaging"** conference once again confirms that packaging safety remains one of the key challenges facing the modern market. In a rapidly evolving regulatory environment, combined with growing consumer expectations and increasing pressure for sustainability, packaging is no longer just a product container. It has become part of a broader system that must simultaneously meet quality, environmental and legal requirements.
For many years, the conference has served as a platform for knowledge exchange between industry professionals, researchers and testing institutions. It is at the intersection of these fields that solutions are developed to address real market needs – from migration and material safety to the challenges of circular economy models. This year's edition places even greater emphasis on a systemic approach, where packaging safety is considered across the entire lifecycle. **Please save the date – November 4-6th 2026, Wroclaw**.
With this issue of "Packaging Review", we aim to provide our readers with insights and research findings that will support informed decision-making and encourage further exploration of packaging's role in a modern, sustainable economy.

Stefan Jakucewicz, D.Sc, Ph.D, Prof. emeritus Warsaw University of Technology. A graduate of Łódź University of Technology in the field of cellulose and paper technology, as well as Warsaw University of Technology in the field of printing. From 1974 he was a researcher at TU Warsaw. Since September 2018 he has been a pensioner. The editor of the sections in the periodicals: Opakowania (Packaging) and Przegląd Papierniczy (Paper Review). Research interests: printing materials science, paper technology and printing techniques of various substrates, with particular emphasis on plastics and the production of printed packaging, production of banknotes and postage stamps (security prints), certification of new base materials for both classic and digital printing techniques. Author or co-author of over 300 scientific articles published in Ukrainian, Slovak and German national journals, and 70 scientific and scientific-technical books published in Polish, German, Slovak and Ukrainian.

Szanowni Państwo,

Kolejna edycja konferencji **„Bezpieczne Opakowanie"** potwierdza, że bezpieczeństwo opakowań pozostaje jednym z kluczowych wyzwań współczesnego rynku. W dynamicznie zmieniającym się otoczeniu regulacyjnym, przy rosnących oczekiwaniach konsumentów oraz coraz większej presji na zrównoważony rozwój, opakowanie przestaje być jedynie nośnikiem produktu. Staje się elementem systemu, który musi jednocześnie spełniać wymagania jakościowe, środowiskowe i prawne.
Konferencja od lat stanowi przestrzeń wymiany wiedzy pomiędzy przedstawicielami przemysłu, nauki oraz instytucji badawczych. To właśnie na styku tych środowisk powstają rozwiązania, które odpowiadają na realne potrzeby rynku – od kwestii migracji substancji, przez bezpieczeństwo materiałowe, aż po wyzwania związane z gospodarką o obiegu zamkniętym. Tegoroczna edycja jeszcze mocniej akcentuje znaczenie podejścia systemowego, w którym bezpieczeństwo opakowania analizowane jest w całym cyklu jego życia. **Zapiszcie Państwo te daty w kalendarzu – 4-6 listopada 2026, Wrocław**.
Oddając w ręce Czytelników kolejny numer „Packaging Review", wierzymy, że prezentowane w nim analizy i wyniki badań staną się inspiracją do dalszych działań oraz pogłębionej refleksji nad rolą opakowania w nowoczesnej gospodarce.

Dr hab. inż. Stefan Jakucewicz, em. prof. PW. Absolwent Politechniki Łódzkiej w zakresie technologii celulozy i papieru oraz Politechniki Warszawskiej w zakresie poligrafii. Od 1974 roku pracownik naukowo-dydaktyczny Politechniki Warszawskiej, od września 2018 emeryt. Redaktor działowy w czasopismach „Opakowanie" i „Przegląd Papierniczy". Zainteresowania naukowe: materiałoznawstwo poligraficzne, technologia papieru oraz techniki drukowania różnych podłoży ze szczególnym uwzględnieniem tworzyw sztucznych i produkcji opakowań drukowanych, produkcji banknotów oraz znaczków pocztowych (druki zabezpieczone), atestacja nowych materiałów podłożowych przeznaczonych tak do klasycznych, jak i cyfrowych technik drukowania. Autor lub współautor ponad 300 artykułów naukowych opublikowanych w czasopismach krajowych, ukraińskich, słowackich i niemieckich oraz 70 książek naukowych i naukowo- technicznych wydanych w językach polskim, niemieckim, słowackim i ukraińskim.

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INNOVATION AS INFRASTRUCTURE IN THE PACKAGING INDUSTRY. THE CASE OF AVERY DENNISON

INNOWACJA JAKO INFRASTRUKTURA W BRANŻY OPAKOWANIOWEJ. PRZYPADEK AVERY DENNISON

ABSTRACT: Innovation in the packaging industry is increasingly shaped by industrial constraints related to scale, regulation, automation, and end-of-life material management. This article examines Avery Dennison as a case illustrating how innovation functions as an infrastructural capability rather than as a sequence of disruptive technological events. Focusing on labels and functional packaging materials, the analysis shows how cumulative advances in materials science, selective integration of digital technologies, and sustainability-driven redesign contribute to systemic change within packaging systems. Through concrete industry examples, the article argues that innovation in packaging is primarily concerned with maintaining operability, compatibility, and adaptability across complex industrial ecosystems.

Key words: packaging innovation; labelling technologies; materials science; RFID; sustainable packaging; industrial systems; circular economy

STRESZCZENIE: Innowacja w branży opakowaniowej jest kształtowana nie tyle przez spektakularne przełomy technologiczne, ile przez konieczność zapewnienia niezawodności, kompatybilności i zdolności adaptacyjnej w obrębie złożonych systemów przemysłowych. Artykuł analizuje firmę Avery Dennison jako przykład pokazujący, że innowacja w sektorze opakowań funkcjonuje przede wszystkim jako zdolność infrastrukturalna zakorzeniona w materiałach, interfejsach i rutynach organizacyjnych. Skupiając się na etykietach oraz funkcjonalnych materiałach opakowaniowych, tekst omawia, w jaki sposób rozwój nauki o materiałach, selektywna cyfryzacja oraz przeprojektowanie zorientowane na zrównoważony rozwój prowadzą do skumulowanej zmiany systemowej. Szczególna uwaga została poświęcona etykietom jako interfejsom operacyjnym łączącym opakowanie z regulacją, logistyką i komunikacją z konsumentem, a także rozwiązaniom RFID, które włączają opakowania w szersze infrastruktury danych. Artykuł pokazuje również, jak presja środowiskowa oraz regionalne zróżnicowanie regulacyjne wpływają na strategie innowacyjne w tej branży. Główna teza brzmi, że w obszarze opakowań innowację należy rozumieć nie jako wytwarzanie nowości dla niej samej, lecz jako ciągłe zarządzanie złożonością przemysłową w warunkach skali, automatyzacji i wymogów gospodarki o obiegu zamkniętym.

Słowa kluczowe: innowacje w opakowaniach; technologie etykietowania; nauka o materiałach; RFID; zrównoważone opakowania; systemy przemysłowe; gospodarka o obiegu zamkniętym

1. PACKAGING INNOVATION UNDER INDUSTRIAL CONSTRAINTS

Innovation in the packaging industry unfolds under conditions that differ fundamentally from those in sectors driven by rapid technological obsolescence. Packaging systems are capital-intensive, optimised for continuous operation, and subject to stringent regulatory oversight. Any innovation must therefore integrate seamlessly into existing filling lines, logistics networks, and waste-management infrastructures. Within this environment, Avery Dennison provides a useful case for analysing how innovation is shaped by constraint rather than by the pursuit of technological disruption.

Incremental innovation dominates this industrial landscape. Minor adjustments in adhesive behaviour, label thickness, or material compatibility can influence line speeds, rejection rates, and recycling outcomes across millions of units. Innovation research characterises this pattern as cumulative innovation, in which marginal improvements produce significant systemic effects over time (Utterback, 1994). In packaging, such cumulative processes form a central source of operational and economic value.

2. MATERIALS SCIENCE IN HIGH-SPEED PACKAGING OPERATIONS

Avery Dennison's innovation capability is grounded in materials science adapted to high-speed, high-volume packaging environments. Pressure-sensitive labels must perform consistently across substrates such as PET bottles, glass containers, aluminium cans, and flexible films. These materials are expected to maintain adhesion under temperature fluctuations, condensation, and mechanical stress, while remaining compatible with automated application systems.

In beverage packaging, for example, labels are exposed to cold-chain conditions that promote moisture formation on container surfaces. Adhesive systems must resist edge lift and flagging while also enabling clean separation during recycling. Innovations addressing this tension illustrate how packaging innovation often involves balancing conflicting performance criteria rather than maximising a single parameter. Such optimisation-oriented innovation aligns with research emphasising robustness and scalability as key sources of value in mature manufacturing sectors (Teece, 2018).

3. LABELS AS FUNCTIONAL INTERFACES WITHIN PACKAGING SYSTEMS

Labels function as critical interfaces within packaging systems, connecting physical containers to regulatory information, logistics processes, and consumer communication. Avery Dennison's innovation strategy reflects this multifunctionality by treating labels as operational components rather than as surface-level design features.

In pharmaceutical packaging, labels must accommodate variable data, including batch numbers, expiry dates, and regulatory language requirements across jurisdictions. Innovations in label construction and print compatibility allow for late-stage customisation, enabling manufacturers to standardise primary packaging while adapting labels at the

PHOTO: AVERY DENNISON

final stages of production. This reduces inventory complexity and regulatory risk without altering core packaging components. Packaging systems research suggests that such interface innovations are essential for managing complexity in globally distributed production networks (Kagermann et al., 2013).

4. INTELLIGENT LABELLING AND DATA-ENABLED PACKAGING

The integration of digital technologies into packaging materials marks a significant development in packaging innovation. RFID-enabled labels developed by Avery Dennison illustrate how packaging components increasingly participate in data infrastructures used in retail and logistics. These labels support automated inventory management, loss prevention, and product authentication.

In apparel and fast-moving consumer goods packaging, item-level RFID enables real-time visibility across distribution centres and retail environments. From a packaging perspective, this introduces additional design constraints, as labels must incorporate electronic components without compromising flexibility, print quality, or recyclability. Empirical studies indicate that the benefits of intelligent packaging depend on organisational adoption and data governance practices, highlighting that such innovations enable rather than determine operational outcomes (Finkenzeller, 2010).

5. SUSTAINABILITY AS A DESIGN CONSTRAINT IN PACKAGING INNOVATION

Sustainability considerations increasingly shape innovation trajectories within the packaging industry. Regulatory frameworks and extended producer responsibility schemes now scrutinise not only primary packaging materials but also auxiliary components such as labels and adhesives. Avery Dennison's innovation activity reflects this shift by embedding environmental criteria into materials development processes.

Examples include linerless labels that reduce waste and adhesive technologies designed to facilitate label removal during recycling. In PET bottle recycling, for instance, adhesives that separate cleanly during washing processes improve material recovery rates. Innovation studies describe such developments as constraint-driven innovation, where environmental pressures lead to incremental yet structurally significant technical change (Porter and van der Linde, 1995).

6. ORGANISATIONAL ADAPTATION TO PACKAGING INDUSTRY COMPLEXITY

The packaging industry operates within a fragmented regulatory and infrastructural landscape. Recycling standards, labelling requirements, and market expectations vary significantly across regions. Avery Dennison's decentralised research and development structure enables regional adaptation while maintaining global material platforms.

Regional teams can tailor materials and label constructions to local requirements without fragmenting the company's technological base. Innovation governance literature suggests that such hybrid organisational models enhance adaptive capacity while preserving economies of scale (Chesbrough, 2003). In packaging, this organisational flexibility is particularly valuable given the uneven pace of regulatory change across markets.

7. CONCLUSION: INNOVATION AS PACKAGING INFRASTRUCTURE

From the perspective of the packaging industry, Avery Dennison's innovativeness is best understood as an infrastructural capability embedded in materials, interfaces, and organisational routines. Innovation is directed towards maintaining system reliability, supporting regulatory compliance, and enabling gradual digitalisation rather than redefining packaging categories.

Labels and functional materials emerge as strategic leverage points within packaging systems, shaping how packages circulate, communicate information, and re-enter material cycles. The analysis demonstrates that innovation in packaging increasingly consists of managing complexity through cumulative, system-oriented development, where progress is measured not by novelty but by sustained operability and long-term adaptability.

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HOW THE D4PACK PROJECT TRANSLATES DATA INTO PACKAGING DECISIONS

JAK PROJEKT D4PACK PRZEKŁADA DANE NA DECYZJE DOTYCZĄCE OPAKOWAŃ

ABSTRACT: The article presents the D4PACK project as a response to increasing complexity in packaging decision-making driven by regulatory, economic and market pressures. It focuses on the Early Guidance Tool (EGeT), a decision-support system developed on the basis of pilot activities with SMEs across Central Europe. The tool enables companies to assess packaging options in terms of technical feasibility, environmental impact, economic aspects and regulatory compliance, and provides a set of realistic alternatives supported by a detailed report. The D4PACK approach demonstrates that structured decision-support is essential for effective and practical implementation of sustainable packaging solutions.
Key words: D4PACK, sustainable packaging, decision-support tools, packaging design, recyclability, PPWR, circular economy, SMEs, agri-food sector, packaging innovation, risk assessment, packaging transition

STRESZCZENIE: Artykuł przedstawia projekt D4PACK jako odpowiedź na rosnącą złożoność podejmowania decyzji dotyczących opakowań, wynikającą z presji regulacyjnych, ekonomicznych i rynkowych. Koncentruje się na narzędziu Early Guidance Tool (EGeT), systemie wspomagania decyzji opracowanym na podstawie działań pilotażowych prowadzonych z udziałem MŚP w Europie Środkowej. Narzędzie umożliwia przedsiębiorstwom ocenę różnych rozwiązań opakowaniowych pod kątem wykonalności technicznej, wpływu na środowisko, aspektów ekonomicznych oraz zgodności z regulacjami, a także dostarcza zestaw realistycznych alternatyw popartych szczegółowym raportem. Podejście D4PACK pokazuje, że ustrukturyzowane wsparcie decyzyjne jest kluczowe dla skutecznego i praktycznego wdrażania zrównoważonych rozwiązań opakowaniowych.
Słowa kluczowe: D4PACK, sustainable packaging, decision-support tools, packaging design, recyclability, PPWR, circular economy, SMEs, agri-food sector, packaging innovation, risk assessment, packaging transition

1. INTRODUCTION

The packaging sector is entering a period of accelerated transformation, driven not by a single factor but by the simultaneous pressure of regulation, market expectations and economic realities. The proposed Packaging and Packaging Waste Regulation (PPWR), increasing requirements linked to recyclability and material reduction, as well as the growing importance of ESG reporting and directives such as CSRD, are fundamentally reshaping how packaging decisions are made. At the same time, companies operate in a volatile economic environment. Raw material prices remain unstable, supply chains continue to adjust, and margins – particularly in the agri-food sector – are under constant pressure. Retailers increasingly introduce their own packaging requirements, often linked to recyclability or material reduction targets. Consumers, on the other hand, expect more sustainable solutions but are rarely willing to accept significant price increases. These factors create a situation in which packaging decisions are no longer linear. They involve multiple, interdependent variables that must be assessed simultaneously – technical, environmental, economic and regulatory.

2. UNDERSTANDING THE PROBLEM: CONSUMER EXPECTATIONS AND MARKET REALITY

The starting point for the development of the D4PACK approach was the market itself. A large-scale consumer study was conducted across Central Europe, involving over 1,000 respondents from multiple countries. The consumer research was conducted by the Department of Packaging and Logistics Processes at the Cracow University of Economics, which provided a comprehensive analysis of consumer expectations and purchasing behaviour in relation to packaging.

The research focused on how consumers perceive packaging, what factors influence their purchasing decisions and how sustainability is positioned relative to price and functionality. The visual appearance of packaging proved to be less important than commonly assumed. This may indicate a growing maturity among consumers, who are becoming increasingly aware of sustainability claims and, at the same time, more sceptical towards superficial "green" messaging. In this sense, the results suggest a certain fatigue with greenwashing and a shift towards more substantive expectations.

The results were clear and, in some aspects, counterintuitive. While environmental aspects are gaining importance, they are not the primary driver of consumer choice. Price and promotions remain the dominant factors, followed by product information and safety-related features. Consumers expect packaging to ensure protection, convenience and usability, including features such as resealability and ease of opening.

Sustainability is relevant, but only within certain limits. Many respondents declared a willingness to choose more environmentally friendly packaging, but only if the price difference remains moderate. This finding highlights a critical constraint for companies: sustainable solutions must not only be environmentally sound, but also economically viable.

3. PHASE 1: LEARNING FROM REAL COMPANIES

The next step in the project was to move from consumer expectations to industrial reality. Phase 1 of the pilot activities involved companies from several Central European countries, representing key sectors such as meat, dairy and fruit and vegetable processing.

Each company was analysed in depth, focusing on one representative product. This allowed for a detailed understanding of packaging systems in real operational conditions. The process included structured interviews and assessments covering product characteristics, packaging formats, production lines, logistical constraints and sustainability ambitions. The pilot activities and the development of the decision-support methodology were led by the Łukasiewicz Research Network – Łódź Institute of Technology, Centre for Circular Economy, which coordinated both the industrial case studies and the transformation of collected data into a structured tool logic.

For each company, alternative packaging solutions were identified and evaluated across multiple dimensions: technical feasibility, environmental impact, economic implications and regulatory compliance. The outcome was not a theoretical recommendation, but a realistic set of possible pathways grounded in actual production environments.

One of the most important findings of this phase was the confirmation that companies across different countries and sectors face very similar challenges. There is a clear intention to move towards more sustainable solutions – particularly recyclable mono-material structures—but this intention is consistently constrained by functional requirements such as barrier performance, mechanical strength and food safety.

At the same time, companies demonstrated a strong focus on short-term operational risks, such as production disruptions or cost increases, while long-term regulatory and environmental risks were often less clearly understood.

These insights became the foundation for the development of the D4PACK tool.

4. FROM PILOT EXPERIENCE TO A PRACTICAL TOOL

A key strength of the D4PACK approach lies in the origin of the proposed solutions. The alternative packaging options included in the tool are not hypothetical or experimental. They are the result of direct discussions with companies, combined with the long-standing expertise of project partners in packaging technology, recyclability and regulatory compliance.

This means that the tool does not direct users towards costly or unrealistic innovations. Instead, it focuses on solutions that are already available on the market, relatively affordable and compatible with existing recycling systems. These include, among others, mono-material polymer structures, recyclable flexible films and selected fibre-based solutions where functional requirements allow.

The intention is not to promote "perfect" packaging, but to support realistic transitions that can be implemented in practice.

5. PHASE 2: STRUCTURE OF THE TOOL

Building on the pilot phase, the project moved into Phase 2, where the decision-support system was implemented as a digital tool.

The tool is structured into two main components. The first is a technological assessment, which evaluates whether a given packaging solution meets functional requirements such as barrier properties, sealing behaviour and compatibility with production lines. The second component focuses on risk analysis, covering economic, environmental, regulatory and operational aspects.

This structure reflects how decisions are actually made in companies, where technical feasibility and risk considerations must be evaluated together.

6. HOW THE TOOL WORKS IN PRACTICE

The D4PACK Early Guidance Tool is a digital decision-support solution designed to help companies evaluate and compare packaging options in a structured and practical way.

The tool is based on real industrial data collected during pilot activities with SMEs across Central Europe, combined with expert knowledge in packaging technology, recyclability and regulatory requirements.

Users are guided through a structured input process describing their product, packaging system and operational constraints. Based on this information, the tool analyses feasibility and risk, and selects three of the most relevant packaging alternatives from its database.

Each analysis results in a detailed report (approx. 30 pages), automatically generated and delivered by email. The report includes a description of alternative solutions, their technical requirements, key limitations and associated risks.

The tool consists of two main modules:

– a technological assessment, evaluating functional feasibility (e.g. barrier properties, sealing, compatibility with production lines),

SELECTION OF PRODUCT SECTOR WITHIN THE D4PACK TOOL INTERFACE (MEAT, DAIRY, FRUIT AND VEGETABLES)

EXAMPLE OF FUNCTIONAL REQUIREMENTS SELECTION IN THE D4PACK TOOL (BARRIER PROPERTIES, USABILITY AND SAFETY PARAMETERS)

– a risk analysis module, covering economic, environmental, regulatory and operational aspects.

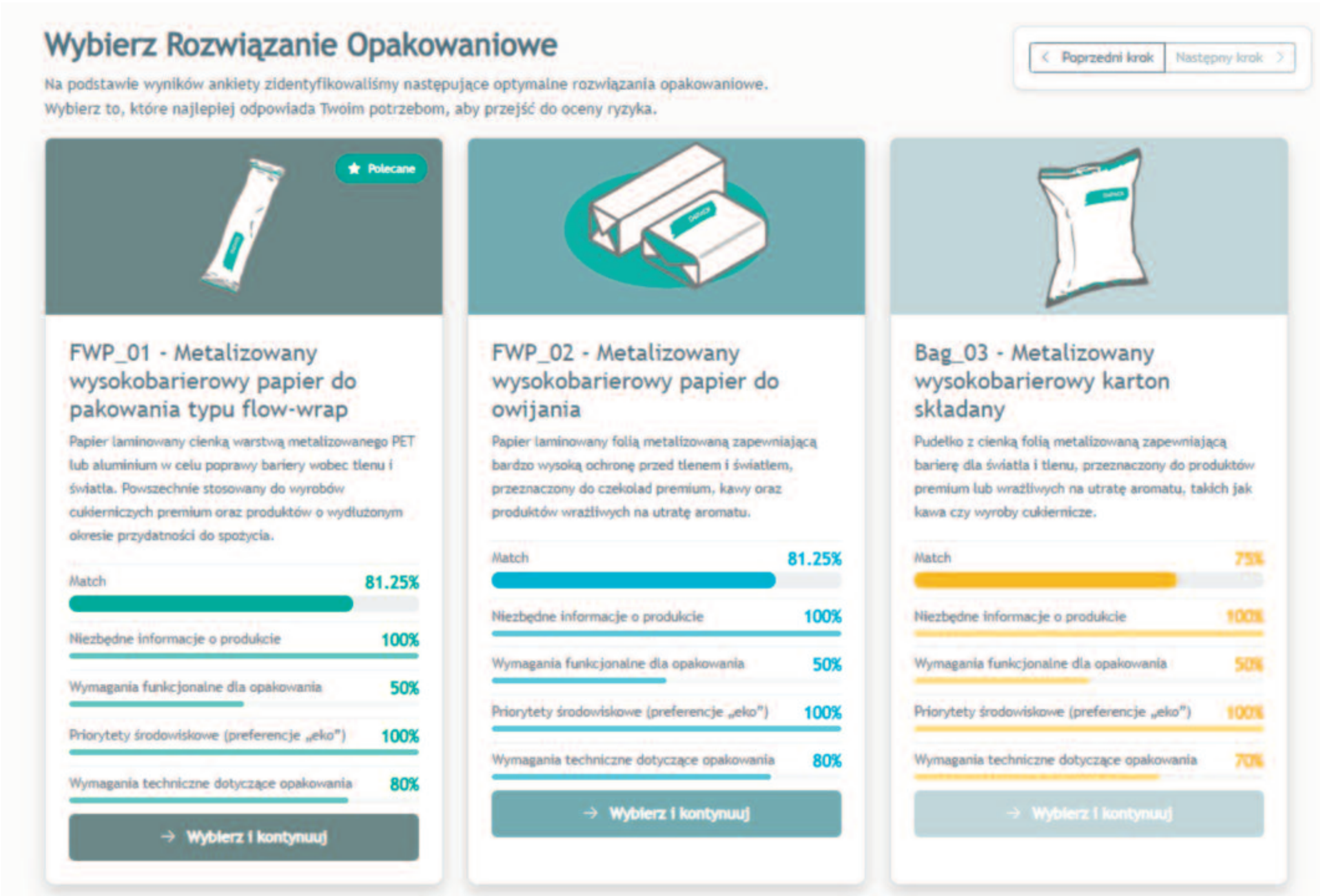
EGeT is available free of charge and can be used multiple times. Users can save progress, return to previous sessions and modify input data, allowing them to explore different scenarios and refine decisions over time. The system is designed as a scalable solution. While currently focused on the agri-food sector, its methodology allows future expansion to other food segments and industries where packaging plays a critical role, including cosmetics or pharmaceuticals. Importantly, the packaging alternatives proposed by the tool are not experimental concepts but market-available solutions, selected for their feasibility, cost-effectiveness and alignment with current recycling systems.

The user begins by entering information about a specific product and its packaging context. This includes product type, packaging format, functional requirements and operational constraints. The system then processes this information using its internal database and decision logic. Based on this analysis, the tool selects three of the most relevant and feasible packaging solutions. Each option is described in detail, including its properties, requirements and limitations. The tool highlights key trade-offs and risks associated with each solution, allowing the user to understand the implications of different choices. The results are compiled into a comprehensive report, typically around 30 pages in length, which is automatically generated and sent to the user by email.

Importantly, the tool is available free of charge. Users can work with it multiple times, explore different scenarios, save their progress and return to modify inputs. This makes it possible to adapt decisions as conditions change or new information becomes available. The system has also been designed with future expansion in mind. While it currently focuses on the agri-food sector, the methodology can be extended to other areas of the food industry, as well as to other sectors where packaging plays a key role, such as cosmetics or pharmaceuticals.

7. CASE STUDY: BALANCING SUSTAINABILITY AND FUNCTIONALITY IN THE MEAT SECTOR

A practical example illustrates how the tool supports decision-making in real conditions. In one of the analysed cases from



EXAMPLE OF RECOMMENDED PACKAGING SOLUTIONS GENERATED BY THE D4PACK TOOL WITH MATCHING SCORES AND REQUIREMENT FULFILMENT LEVELS

the meat sector, the company used a multi-layer packaging structure for modified atmosphere packaging (MAP), ensuring extended shelf life and high product safety.

The company's objective was to reduce plastic use and improve recyclability. At first glance, fibre-based solutions appeared to be an attractive alternative. However, a detailed assessment showed that such solutions were not able to provide the required barrier performance or prevent leakage under real conditions.

The tool identified mono-material polyethylene-based solutions as a more realistic alternative. While these solutions did not eliminate plastic entirely, they significantly improved recyclability and maintained compatibility with existing production lines. Most importantly, they ensured that food safety and shelf-life requirements were not compromised.

This example demonstrates a key principle of the D4PACK approach. The goal is not to replace one material with another in a simplistic way, but to find solutions that balance sustainability with functionality and economic feasibility.

8. FROM INTUITION TO STRUCTURED DECISION-MAKING

The experience gained within the D4PACK project clearly shows that the main barrier to sustainable packaging is not the lack of available solutions, but rather the lack of structured and transparent decision-making processes. In practice, companies are often aware of the direction in which they should move — towards improved recyclability, reduced material use or better environmental performance — but they face significant difficulties when it comes to evaluating and comparing different options in a comprehensive and reliable way.

This challenge stems from the inherently multi-dimensional nature of packaging. Any change in material or structure has consequences not only for environmental performance, but also for product safety, shelf life, production processes, logistics and overall costs. Without a framework that allows these aspects to be assessed simultaneously, decisions tend to be fragmented, based on partial information or influenced by external pressures, such as supplier recommendations or retailer requirements.

By integrating technical, environmental, economic and regulatory aspects into a single, coherent framework, the D4PACK tool enables a more systematic and evidence-based approach to decision-making. It allows companies to move beyond simplified or one-dimensional evaluations and instead consider packaging as part of a broader system, where trade-offs must be identified and managed rather than ignored.

This shift from intuitive decision-making to structured analysis is particularly important in the current environment. Increasing regulatory requirements, evolving market expectations and economic uncertainty mean that incorrect decisions can lead not only to operational inefficiencies, but also to significant long-term consequences, including additional costs, compliance risks and the need for repeated adjustments in the future.

9. CONCLUSION

The transformation of the packaging sector is often discussed in terms of materials and technologies. While these are undoubtedly important, the D4PACK project highlights another critical aspect: the ability to navigate complexity and make informed decisions. By combining real industry data, practical experience and a structured methodology, the D4PACK tool provides tangible support for companies facing this challenge. It does not eliminate complexity, but it makes it manageable. In a context where sustainability must be aligned with functionality, cost and regulation, this ability may prove to be one of the most valuable assets for the industry in the years ahead.

THE CHART PRESENTS A SYNTHETIC OVERVIEW OF THE AVERAGE RISK LEVEL ACROSS KEY FACTORS, INCLUDING ECONOMIC, ENVIRONMENTAL AND SOCIAL ASPECTS, PACKAGING QUALITY AND PERFORMANCE, REGULATORY COMPLIANCE AND TECHNICAL FEASIBILITY

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Access to the tool. Below you will find a QR code and a direct link to the D4PACK Early Guidance Tool (EGeT). Access requires providing an email address, to which the generated report will be sent. The tool can be used multiple times, allowing users to explore different scenarios and refine their inputs.
https://d4packtool.eu/login

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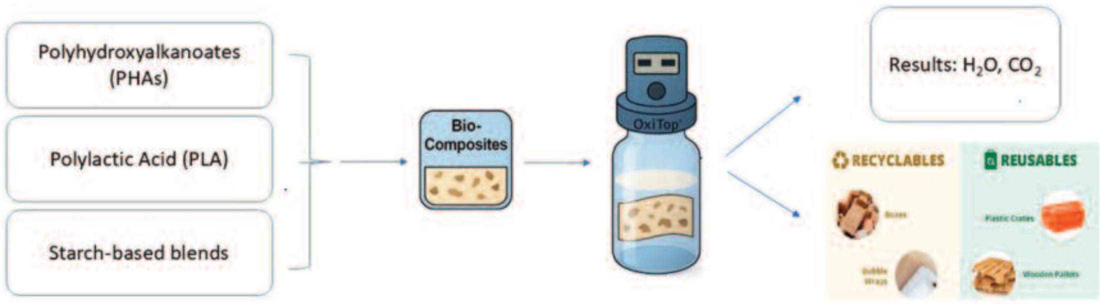
OXITOP SYSTEM FOR AEROBIC DEGRADATION OF BIODEGRADABLE POLYMER BIO-COMPOSITES IN SUSTAINABLE PACKAGING APPLICATIONS

SYSTEM OXITOP DO OCENY TLENOWEJ DEGRADACJI BIODEGRADOWALNYCH KOMPOZYTÓW POLIMEROWYCH WSPIERAJĄCYCH ZRÓWNOWAŻONY ROZWÓJ OPAKOWAŃ

ABSTRACT: The rising impact of plastic pollution have led to an effort for environment friendly and effective packaging materials. Biodegradable polymers and their composites reinforced with waste natural fillers offer a strong potential to replace conventional plastic among the new alternatives. But how well they break down in oxygen rich environment determines their success. The OxiTop® respirometric system offers a simple and reliable way to measure this process by tracking microbial oxygen use and carbon dioxide release. In this review, an overview is provided of the structural and chemical factors influencing the aerobic biodegradation of key polymers such as Polyhydroxyalkanoates (PHAs), Polylactic acid (PLA), and starch- based blends along with the function of natural fillers in changing mechanical characteristics and degradation kinetics. It also outlines how OxiTop® testing helps compare biodegradation behaviour and supports the design of new materials. This review addresses the potential of biodegradable bio-composites as practical choices for sustainable and circular packaging by connecting lab data with real composting performance.
Key words: biodegradable polymers, Bio-composites, Aerobic degradation, OxiTop® respirometry, Sustainable packaging

STRESZCZENIE: Wzrost zanieczyszczenia środowiska tworzywami sztucznymi spowodował zwiększoną działalność na rzecz rozwoju ekologicznych i wydajnych materiałów opakowaniowych. Biodegradowalne polimery oraz ich kompozyty wzmocnione naturalnymi wypełniaczami pochodzącymi z odpadów mają duży potencjał na zastąpienie tradycyjnych tworzyw sztucznych wśród nowych rozwiązań alternatywnych. Jednak to, jak dobrze rozkładają się w środowisku bogatym w tlen, decyduje o ich sukcesie. System respirometryczny OxiTop® oferuje prosty i niezawodny sposób pomiaru tego procesu poprzez śledzenie mikrobiologicznego zużycia tlenu i uwalniania dwutlenku węgla. W niniejszym opracowaniu przeanalizowano czynniki strukturalne i chemiczne mające wpływ na biodegradację tlenową kluczowych polimerów, takich jak polihydroksyalkaniany (PHA), polilaktyd (PLA) oraz mieszaniny oparte na skrobi, a także rolę naturalnych wypełniaczy w modyfikacji właściwości mechanicznych i kinetyki degradacji. W artykule opisano również, w jaki sposób testy OxiTop® pomagają porównywać biodegradowalność i wspierają projektowanie nowych materiałów. Niniejszy przegląd analizuje potencjał biodegradowalnych biokompozytów jako praktycznego rozwiązania dla zrównoważonych opakowań, łącząc dane laboratoryjne z rzeczywistą wydajnością kompostowania.
Słowa kluczowe: polimery biodegradowalne, biokompozyty, degradacja tlenowa, respirometria OxiTop®, zrównoważone opakowania



GRAPHICAL ABSTRACT

1. INTRODUCTION

Plastic packaging is integral to modern food distribution and consumer goods, but its persistence has become a defining sustainability challenge. Conventional, petroleum-based plastics resist microbial attack and can accumulate in terrestrial and marine environments for decades [1]. In response, research has pivoted to biodegradable polymers materials derived from renewable resources that are designed to decompose under controlled composting or other oxygen-rich conditions, returning carbon to the biosphere as CO_2 and water [2] [3] [4]. The packaging sector remains the largest outlet for plastics in Europe, representing 39–40 % of demand, making it a strategic entry point for compostable solutions [5]. Biodegradable systems such as polyhydroxyalkanoates (PHAs), polylactic acid (PLA), poly(butylene adipate-co-terephthalate) (PBAT), poly(butylene succinate) (PBS) and starch-based polymers combine renewable feedstocks with potential end-of-life biodegradability, though adoption has been tempered by cost, brittleness, and variable performance in real composting environments [6].

A promising approach is to design bio-composites in which biodegradable polymers are reinforced with natural or low-value industrial waste fillers. Incorporating residues such as wood flour, rice husk, beetroot powder, or spent coffee grounds can increase stiffness and sometimes toughness, while at the same time creating value from materials that would otherwise be discarded. This strategy not only tailors the performance of the polymer matrix but also supports a circular economy by closing material loops and reducing waste[7] [8]. Yet their environmental relevance depends not only on renewable origin but on verified aerobic biodegradation rates [9] and alignment with standardized composting tests (ISO 14855-1) [10]. Among available tools, the OxiTop® respirometric system offers a direct, reproducible way to monitor microbial respiration by tracking oxygen uptake (with CO_2 trapped) in sealed vessels containing a polymer sample and active inoculum. This setup yields continuous, interpretable biodegradation kinetics without complex instrumentation [11] [12]. Consequently, OxiTop® is well-suited for comparative studies of bio-composites, where filler chemistry and loading can be correlated to changes in lag time and oxygen-consumption rates key indicators for performance in composting and sustainable-packaging applications [13] .

2. BIODEGRADABLE POLYMERS FOR SUSTAINABLE PACKAGING

Biodegradable polymers combine renewable origin with the capacity to decompose into natural metabolites after disposal. They can be converted into films, trays, and coatings using the same processing routes as conventional plastics. Biodegradation is intended only after the packaging is discarded and enters an end-of-life pathway where suitable conditions (temperature, moisture, oxygen and active microorganisms) are present [14]. For sustainable packaging, the most widely studied systems include Polyhydroxyalkanoates (PHAs), Polylactic acid (PLA), starch-based blends, and Poly(butylene adipate-co-terephthalate) (PBAT) which is flexible synthesized aliphatic aromatic biodegradable copolyester [15] and aliphatic biodegradable polyester i.e Poly(butylene succinate) (PBS) [16].

2.1. POLYHYDROXYALKANOATES (PHAs)

Polyhydroxyalkanoates (PHAs) are a family of biodegradable polyesters that many bacteria accumulate intracellularly when essential nutrients such as nitrogen or phosphorus become limited but carbon is still available [17]. Depending on the type and ratio of their monomeric units most commonly 3-hydroxybutyrate, 4-hydroxybutyrate, or 3-hydroxyvalerate these polymers can exhibit a wide range of mechanical behaviours, from rigid and brittle to soft and elastic. PHAs are noted for their excellent oxygen-barrier properties and their capacity to undergo complete biodegradation in soil, marine, and compost environments [18]. Under aerobic conditions, extracellular depolymerase enzymes secreted by microorganisms hydrolyse the ester backbone, generating soluble oligomers and monomers that are subsequently oxidised to carbon dioxide and water [19]. To mitigate their brittleness and production cost, PHAs are often blended with other biodegradable polymers or reinforced with low cost or waste derieved natural fillers, yielding composite packaging materials that combine satisfactory mechanical performance with verified compostability [20,21].

2.2. POLYLACTIC ACID (PLA)

PLA is synthesized via fermentation of sugars or starch followed by polymerization of lactic acid. It exhibits high clarity and rigidity comparable to polystyrene, making it suitable for food trays and transparent films [22]. However, PLA's brittleness and slow hydrolysis at ambient temperature limit its end-of-life performance [23-25]. Under controlled composting (55-60 °C, high humidity), PLA hydrolyzes into lactic acid, which is readily metabolized by microorganisms helps in acceleration of biodegradation [26]. Blending with PBAT or PBS increases flexibility and can accelerates disintegration under industrial composting depending on the blending ratio, morphology, fillers, and article thickness [27-29]. Because of its defined chemistry, PLA serves as a reference polymer for evaluating aerobic biodegradation kinetics in OxiTop® experiments [30].

2.3. STARCH-BASED MATERIALS

Starch, a natural polysaccharide from agricultural sources, can be thermoplastically processed when plasticized with glycerol or sorbitol. Thermoplastic starch (TPS) is inexpensive, fully compostable, and compatible with hydrophilic fillers. Its hydrophilicity promotes rapid water uptake and microbial colonization, resulting in accelerated aerobic degradation [31]. Blending TPS with aliphatic polyesters balances mechanical strength with degradability, providing flexible packaging materials that decompose completely in compost within a few weeks [32].

TABLE 1: REPRESENTATIVE BIODEGRADABLE POLYMERS FOR SUSTAINABLE PACKAGING

Polymer	Origin / Type	Key Attributes	Aerobic Degradation Behaviour	Typical Packaging Use	Source
PHA	Microbial fermentation of renewable feedstocks	High oxygen barrier, biocompatible	Rapid enzymatic hydrolysis → mineralization in compost/soil	Coated paper, trays, bottles	[6]
PLA	Fermented sugars/starch → polymerized to PLA	Transparent, stiff; needs toughening	Hydrolysis to lactic acid → microbial assimilation under aerobic composting; kinetics tunable by blends	Rigid cups, thermoformed trays, films	[37]
TPS (Starch)	Natural polysaccharide plasticized (e.g., glycerol)	Hydrophilic, inexpensive, renewable	Fast microbial oxidation; complete mineralization feasible in compost	Films, carrier bags, cushioning	[38]
PBAT	Synthetic aliphatic–aromatic copolyester	Flexible, ductile; blend partner for PLA/starch	Moderate-to-fast aerobic degradation; compostable blends common	Compostable bags, wraps	[39]
PBS	Synthetic aliphatic polyester (succinate-based)	Heat-resistant, tough	Steady hydrolytic/enzymatic degradation under aerobic composting	Foams, molded items, films	[40]

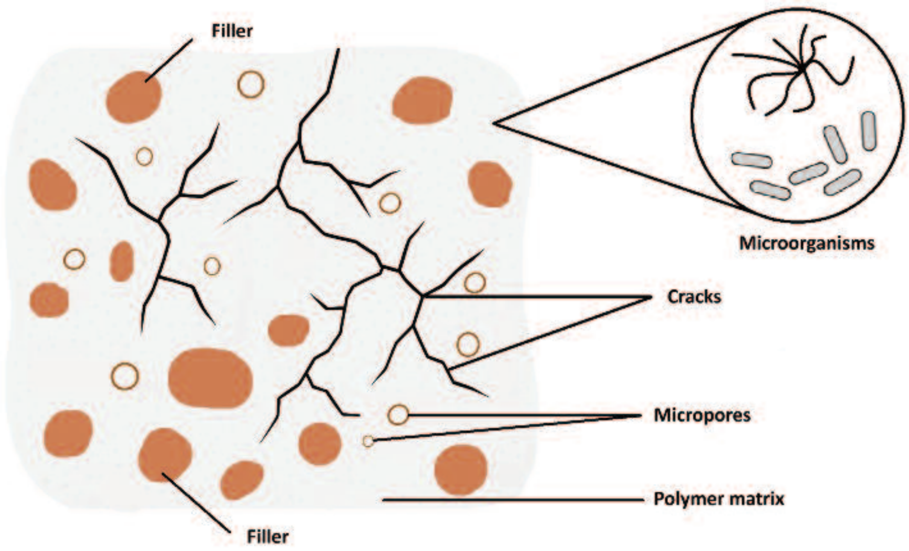


FIGURE 1: SCHEMATIC SHOWING FILLER-INDUCED POROSITY AND MICROBIAL ACCESS PATHWAYS.

2.4. SYNTHETIC BIODEGRADABLE POLYESTERS

PBAT and PBS are synthetic yet biodegradable copolyesters designed to complement bio-based matrices. PBAT provides elasticity and toughness, whereas PBS contributes heat resistance [33,34]. Both degrade aerobically through hydrolytic chain scission followed by microbial oxidation of the resulting fragments [35]. When combined with PLA or starch, they yield films that match the performance of conventional plastics but maintain compostability [36].

3. BIO-COMPOSITES REINFORCED WITH WASTE NATURAL FILLERS

Blending biodegradable polymers with agricultural or industrial residues transforms waste into functional reinforcements while reducing material cost and carbon footprint [41]. These bio-composites exemplify circular-economy practice; the filler valorizes organic by-products, and the polymer matrix ensures controlled degradation after use.

3.1. STRUCTURE AND INTERFACE MECHANISM

Natural fillers such as wood flour, rice husk, spent coffee grounds, or beetroot residues consist mainly of cellulose, hemicellulose, and lignin. These biopolymers present abundant hydroxyl and carboxyl groups that interact with polar biodegradable matrices through hydrogen bonding or limited esterification during melt processing. Such interfacial interactions improve stiffness, modulus, and dimensional stability by restricting polymer-chain mobility [42] [43]. At the same time, the hydrophilic nature of the fillers promotes water uptake within the composite, which becomes advantageous under aerobic degradation conditions. The absorbed moisture accelerates hydrolytic cleavage of ester bonds and supports microbial colonisation on the filler matrix boundary, where enzymes initiate polymer breakdown [44]. As a result, bio-composites containing roughly 10–30 wt % of lignocellulosic filler typically exhibit shorter induction periods and higher oxygen-consumption rates in respirometric tests compared with neat polymers [45].

3.2. REPRESENTATIVE SYSTEMS AND PERFORMANCE

- PHA (PHBV) + wood flour: Increased modulus and faster mineralization under compost conditions [46].
- PLA + beetroot powder: Natural coloration and enhanced CO_2 evolution during degradation [47].

These systems demonstrate that filler selection can tune both mechanical and biodegradation performance to match packaging needs.

3.3. PROCESSING AND ENVIRONMENTAL RELEVANCE

Melt compounding with a twin-screw extruder is the most effective technique for preparing polymer bio-composites because it promotes uniform filler dispersion while limiting

TABLE 2: SELECTED POLYMER FILLER BIO-COMPOSITES AND AEROBIC DEGRADATION TRENDS

Polymer matrix	Filler	Origin	Mechanical effect	Aerobic-degradation trend	Packaging	References relevance
PHBV (or P(3HB-co-4HB))	Wood flour / wood fibers	Sawdust / wood-processing waste	↑ Modulus, ↓ Elongation	Faster mass loss and respiration vs. neat PHA under soil/ /compost-like aerobic conditions	Rigid trays, caps	[45], [48]
PHBV	Spent coffee grounds (SCG)	Beverage-industry residue	↑ Thermal stability; tunable stiffness	Earlier microbial activity / accelerated degradation vs. neat PHBV (lab compost/soil)	Cups, lids	[49]
PLA	Beetroot pulp / pomace	Food-processing waste	Natural coloration; ↑ UV resistance; ↑ stiffness with compatibiliser	Higher CO_2 evolution / faster disintegration vs. neat PLA in controlled compost	Decorative films, trays	[50]
PLA/PBAT (blend)	Rice husk	Rice-milling residue	↑ Toughness; ↓ material cost	Accelerated degradation vs. neat PLA under compost-like conditions	Flexible wraps, compostable bags	[51]
TPS/PCL (blend)	Fruit-peel derivatives (citrus peel powder)	Citrus-processing waste	↑ Elongation (from PCL), added antioxidant function	Full mineralisation achievable in compost; fruit-peel fillers promote wettability/microbial access	Compostable liners, produce bags	[38], [52]

thermal degradation of the matrix when temperatures are kept below about 180 °C [53] [54]. Proper drying of lignocellulosic fillers before processing is essential to avoid moisture-induced hydrolysis of ester bonds, which can otherwise lower molecular weight and mechanical strength [55]. To improve compatibility between hydrophilic fibers and hydrophobic polymer matrices, several environmentally friendly surface treatments have been proposed. Mild organic-acid modification particularly with citric acid or enzymatic esterification using lipases can increase interfacial adhesion without reducing the final material's biodegradability [56] [57]. From a sustainability perspective, life-cycle-assessment studies indicate that substituting roughly 20–30 wt% of the neat biodegradable polymer (e.g. PLA, PHAs, PBS or PBAT) with lignocellulosic by-products which can lower the greenhouse gas emissions compared with using the polymer alone [58,59].

3.4. CONNECTION TO OXITOP® ANALYSIS

Because OxiTop® directly records oxygen uptake, it captures how fillers influence biodegradation kinetics. Materials with higher filler content typically reach maximum respiration sooner and display greater total oxygen demand [60] [61]. Such data verify that waste fillers act not only as structural reinforcements but also as promoters of aerobic biodegradation, aligning composite performance with sustainable packaging goals.

4. MECHANISM OF AEROBIC DEGRADATION AND OXITOP® TESTING APPROACHES

4.1. STAGES OF AEROBIC DEGRADATION

Biodegradable polymers undergo a well-defined multistage process when exposed to oxygen rich environments.

1. Fragmentation: Physical stresses, moisture absorption, and thermal fluctuations produce cracks that enlarge the surface area available for microbial colonisation [62].
2. Depolymerisation: Extracellular enzymes secreted by bacteria or fungi hydrolyse ester linkages, yielding soluble oligomers and monomers such as lactic acid (from PLA) or 3-hydroxybutyric acid (from PHB type PHAs) and 3-hydroxyvaleric acid (from PHBV type PHAs) [63–65].
3. Assimilation and Mineralisation: Microorganisms metabolise these low-molecular-weight intermediates through oxidative

pathways, releasing carbon dioxide, water, and biomass [66] [67] .

The rate and completeness of this sequence depend on polymer chemistry, crystallinity, filler composition, temperature, humidity, and microbial population [68]. In bio-composites, hydrophilic natural fillers accelerate moisture diffusion and enzyme penetration, shortening the induction (lag) period before oxygen consumption begins [62] [69].

4.2. ROLE OF FILLER MORPHOLOGY AND INTERFACE

The presence of lignocellulosic fillers modifies degradation behaviour in two complementary ways. Structurally, they introduce discontinuities that promote crack propagation and localised oxygen access [70] [71]. Chemically, hydroxyl and carbonyl groups on filler surfaces act as initiation points for hydrolysis and microbial adhesion. When degradation progresses, voids form around filler particles, creating new channels for oxygen diffusion and microbial growth [72] [45]. Consequently, composites containing 10–30 wt % of coffee-ground residues often exhibit steeper oxygen-uptake curves and higher cumulative CO_2 release than unfilled polymers in OxiTop® experiments [73] [74].

4.3. ANALYTICAL APPROACHES TO QUANTIFY AEROBIC BIODEGRADATION

Traditional tests such as mass-loss measurements or CO_2-evolution assays provide useful end-point data but lack continuous kinetic resolution. Modern respirometric techniques overcome this limitation by monitoring gaseous exchange in real time [75]. Among them, the OxiTop® Control system has become one of the most reliable laboratory tools for determining aerobic biodegradation rates of polymeric materials [76].

In the OxiTop® method, polymer samples are incubated with a microbial inoculum (typically mature compost or activated sludge) in sealed glass reactors equipped with digital pressure sensors. A CO_2 absorber commonly sodium-hydroxide pellets is placed inside the headspace so that only oxygen uptake influences internal pressure. As microorganisms oxidise the sample's organic carbon, the drop in pressure is recorded automatically at set intervals, generating an oxygen-consumption curve that reflects microbial respiration [77].

4.4. DATA INTERPRETATION AND KINETIC PROFILES

Typical OxiTop® curves exhibit three distinct regions:

- Lag phase: microbial adaptation to the substrate;
- Exponential phase: rapid enzymatic degradation and high oxygen uptake;
- Plateau: stabilisation once readily degradable carbon is exhausted [78].

From these regions, the oxygen-uptake rate (OUR) and total oxygen demand (TOD) can be calculated, allowing estimation of the percentage of theoretical biodegradation. Comparative tests of pure polymers and their bio-composites reveal that filler addition not only increases the slope of the exponential phase but also reduces the lag period, confirming enhanced microbial accessibility [79]. For instance, PHBV wood

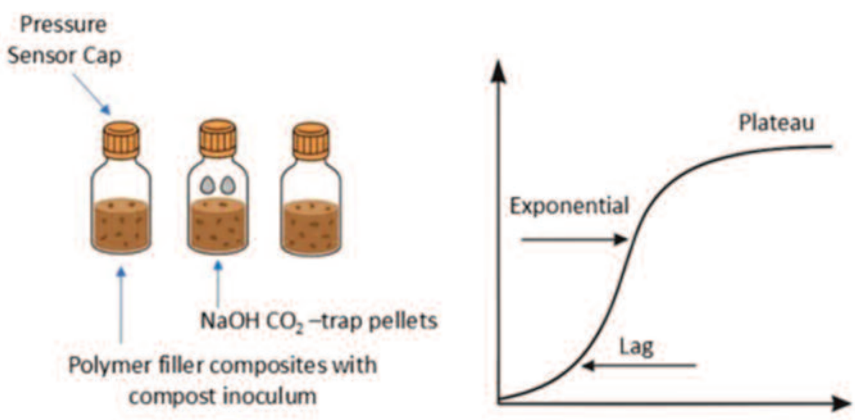


FIGURE 2: SCHEMATIC REPRESENTATION OF THE OXITOP® SETUP AND TYPICAL OXYGEN-CONSUMPTION CURVE.

composites typically reach 80 % mineralisation within 40 days, whereas neat PHBV requires nearly twice that duration under identical conditions [80].

3.5..ADVANTAGES AND LIMITATIONS OF THE OXITOP® SYSTEM

OxiTop® respirometry offers multiple benefits including continuous, non-invasive monitoring of oxygen consumption; reproducibility across parallel samples; simple correlation between pressure change and biodegradation degree; minimal handling, reducing contamination risk [81]. However, it simulates controlled aerobic composting rather than open environment conditions, and results can vary with inoculum activity or nutrient composition. Volatile intermediates that escape CO_2 absorption may slightly affect pressure readings. For comprehensive assessment, OxiTop® data are best complemented by gravimetric or CO_2-evolution tests to confirm total mineralisation [82].

4.7. RELEVANCE TO SUSTAINABLE PACKAGING

Quantitative oxygen-consumption data from OxiTop® testing bridge material formulation with real composting performance. The method enables developers to tailor polymer filler ratios and processing conditions to achieve targeted degradation times, aligning product lifespan with disposal pathway [75]. Integration of such respirometric evaluation into eco design and certification frameworks ensures that emerging bio-composites fulfil their promise as truly sustainable packaging materials within the circular-economy model [13].

5. FACTORS INFLUENCING AEROBIC BIODEGRADATION

Aerobic degradation of biodegradable polymer bio-composites is a complex interplay of material and environmental parameters that govern microbial activity, oxygen transfer, and polymer accessibility. Understanding these relationships is essential for interpreting OxiTop® data and optimizing formulations for sustainable-packaging applications [62].

5.1. ENVIRONMENTAL PARAMETERS

Temperature strongly affects enzymatic and microbial kinetics. Composting systems maintained between 50 and 60 °C exhibit the highest oxygen-uptake rates for PHAs and PLA blends, while lower ambient temperatures slow hydrolysis and prolong the lag phase [83] [84].

Moisture content ensures diffusion of nutrients and enzymes through the polymer matrix; values below 40% relative humidity markedly reduce microbial colonisation.

Adequate aeration prevents local oxygen depletion, maintaining oxidative metabolism instead of partial anaerobiosis that can generate methane. Finally, microbial diversity in the inoculum determines degradation pathways mixed bacterial and fungal consortia generally outperform single strains in mineralising complex composites [85].

5.2. MATERIAL-RELATED PARAMETERS

Inherent polymer properties such as crystallinity, molecular weight, and surface hydrophilicity dictate degradation kinetics. Amorphous regions hydrolyse faster than crystalline domains, and lower molecular weight chains are more susceptible to enzymatic attack [86]. The incorporation of hydrophilic natural fillers wood flour, rice husk, or coffee residues enhances water uptake and oxygen diffusion, thereby accelerating microbial oxidation [80] [87]. Conversely, excessive filler loading or poor interfacial adhesion may create impermeable zones that hinder oxygen penetration.

Particle size also plays a decisive role: smaller particles disperse more uniformly and increase the reactive surface area, whereas larger fragments act as inert inclusions. Surface modification of fillers by mild organic acids or silane coupling agents improves bonding and mechanical stability without suppressing biodegradability [88]. In OxiTop® curves, these factors manifest as variations in the slope and amplitude of oxygen-consumption profiles [62].

5.3. PROCESSING AND ADDITIVES

Processing conditions such as extrusion temperature, shear rate, and cooling rate influence polymer crystallinity and hence degradation behaviour. Plasticisers and compatibilisers can modify moisture affinity or microbial recognition sites, either promoting or delaying mineralisation [89]. The use of bio-based additives citric acid, natural waxes, or enzymatically grafted oligomers tends to preserve compostability while enhancing flexibility and surface wettability [90] [53] [91].

5.4. INTEGRATIVE PERSPECTIVE

Optimising aerobic degradation requires balancing mechanical performance with environmental disintegration [92]. OxiTop® measurements provide rapid feedback on how each parameter affects the oxygen-consumption rate, enabling rational design of packaging materials that degrade at desired timescales under industrial or home composting conditions [93]. By systematically correlating formulation variables with respirometric data, researchers can establish predictive models to guide the next generation of biodegradable bio-composites.

6. CONCLUSIONS AND FUTURE OUTLOOK

One important aspect for generating sustainable packaging solutions is getting switched from conventional plastics to biodegradable polymer bio-composites. These materials offer mechanical strength, a lower environmental impact, and in accordance with circular economy practices by combining renewable feedstocks with functional reinforcements made from industrial and agricultural waste. However, their actual sustainability relies on their shown degradability on oxygen rich (aerobic) conditions and when applicable their ability to behave in oxygen limited (anaerobic) conditions which may proceeds more slowly and result in generation of biogas. The OxiTop® respirometric method provides a reliable, quantitative approach for assessing aerobic biodegradation through continuous monitoring of oxygen consumption and carbon-dioxide evolution. In comparison to conventional static assays, it yields repeatable kinetic profiles that account for the effects of environmental factors, filler type, and polymer chemistry. The method's simplicity and accuracy make it perfect for integrating lab findings with industrial composting performance and screening novel bio-composites formulations. Future research should focus on correlating OxiTop® data with molecular level degradation pathways to establish predictive models that connect material design, processing conditions, and environmental fate. Expanding the database of polymer filler combinations tested under standardized OxiTop® conditions will enable the creation of benchmarks for certification and eco design. The next generation of bio-composites will be further ensured to meet ecological and functional requirements by combining respirometric data with life cycle assessment and mechanical durability tests. The packaging industry may get closer to closed-loop, zero waste concept where bio-composites not only perform well but also securely return to nature at the end of their lifecycle by combining material innovation with comprehensive biodegradation testing.

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URSZULA SZELUGA

WORKSHOP ON MULTIFUNCTIONAL POLYMER COMPOSITE MATERIALS FOR ADVANCED APPLICATIONS

On March 26, 2026, the International Workshop on „Multifunctional Polymer Composite Materials for Advanced Applications „was held in Zabrze. The workshop was organized by the Centre of Polymer and Carbon Materials of the Polish Academy of Sciences and was supported by the National Agency under the Welcome to Poland project no. BNP/WTP/2023/1/00015 entitled „International promotion of the CMPW PAN in the integration of doctoral students in the field of advanced polymer materials".

The aim of the workshop was to create an international platform for the exchange of knowledge and experience in the field of modern polymer based composite materials and their versatile, tailor-made functionalities and applications. It was addressed to PhD students and young researchers conducting studies both on the new functional polymers, new functional addivitives, primarily active fillers of different structure and chemical nature, leading to modern composite materials. The workshop area focused also on the characteristics of structure and functional properties, the processing and design of modern systems, and innovative applications in electronic systems, sensors, medicine, and engineering structures.

During the workshop, young researchers had the opportunity to attend three invited lectures on the importance of polymer based multifunctional polymer composites:

1. Sébastien Pruvost and Aurélien Roggero -„Dielectric spectroscopy in polymers and composites: molecular mobility and characterization of interfaces" (Université de

Lyon, CNRS, Université Claude Bernard Lyon 1, INSA Lyon, Université Jean Monnet, UMR 5223, Ingénierie des Matériaux Polymères)

2. Róża Tomikowska „Thermal analysis techniques (DSC, TGA, STA) as a tool for characterization of polymer and composite materials„(Haas Company, Poznań)
3. Paweł Wróbel „Nanomaterials as a building block of modern composites and hybrid systems: synthesis and characterization" (Centre of Polymer and Carbon Materials, Polish Academy of Sciences, Zabrze)

The workshop included 9 oral presentations prepared by polish and foreign doctoral students from Czech Republic, Romania, France, Bulgaria, presenting the results of research conducted as part of their doctoral theses.

During the poster session, participants had the opportunity to exchange knowledge with expirienced speakers, and other doctoral students to promote interdisciplinary collaboration and the joint research for future-oriented solutions.

A practical workshop on the use of thermal analysis techniques and data analysis, led by Róża Tomikowska of Haas Company, provided participants with real-life contact with the experimental challenges involved in characterizing polymers and polymer composites.

The scientific importance and significance of this event—which focused on current research on composite materials and provided an opportunity for doctoral students from Poland and abroad to meet and exchange experiences—should be emphasized. This development is of key importance for next-generation technologies, such as flexible electronics, energy harvesting systems, and smart materials for the aerospace, military, automotive, and many other industries.

Website of the event:

https://cmpw-pan. pl/2026/02/09/workshop-3/

PHOTO BY ANNA GAWRON

BEVERAGE PACKAGING IS BECOMING LIGHTWEIGHT

As the world's leading trade fair for processing and packaging solutions, interpack will once again bring together the international players involved in bottling, canning and packaging beverages in 2026. This sector, too, is currently driven by regulatory requirements such as the European Packaging and Packaging Waste Regulation, ambitious sustainability targets set by manufacturers and changes in consumer behaviour.

Traditional beverage packaging such as bottles made from glass or PET, aluminium cans and drinks cartons are changing: today, a maximum reduction in material, intelligent barrier functions, digital process control and improved recyclability are among the requirements for new generations of beverage packaging systems.

Weight reduction is a major topic. interpack exhibitor KHS, for example, is pursuing a "premium lightweight" approach and presents Premium Lite, a bottle for still mineral water made of 100 per cent recycled PET, weighing in at just 6.2 grams for 0.25 litres. The new bottle is designed to combine a minimum use of materials with high-quality aesthetics and has been specifically tailored to the requirements of modern high-speed production lines. This lightweight is produced on the advanced KHS InnoPET Blomax Series V stretch blow-moulding machine, which ensures process stability for large quantities with high precision.

When it comes to product protection and the circular economy, KHS is taking things even further with its new Supreme PET bottle. Here, the company employs its own Plasmax technology, which applies a silicon oxide coating that is less than 100 nanometres thick to the bottle's inner wall. The coating acts like glass, protecting oxygen-sensitive drinks – such as high-quality green tea – from oxidation and extending their shelf lives many times over. At the same time, the bottle is still fully recyclable, as during the recycling process, the glass layer is removed in an alkaline solution without contaminating the PET. The combination of maximum product protection, rPET compatibility and industrial production speeds of up to 60,000 bottles per hour illustrates the extent to which barrier technologies have now evolved towards a circular economy.

EASILY RECYCLABLE LABELS

Along with a reduction in materials, the question of the recyclability of individual components is becoming increasingly

KHS SUPREME COMBINES PET WITH A WAFER-THIN INNER COATING OF GLASS. IMAGE: KHS

THE ECOFLOAT WHITE OPTION ALLOWS BOTTLERS TO SWITCH FROM OPAQUE HDPE OR PET PACKAGING TO CLEAR PET BOTTLES. IMAGE: CCL LABEL

important. As an exhibitor at interpack 2026, CCL Label focuses on innovations in the circular economy and shows how packaging design can actively support recycling systems. In the area of label and sleeve technology, the company opts for concepts that support recycling. EcoFloat, for example, is a shrink sleeve solution based on low-density polyolefin. During the sink float PET recycling process, the sleeve material floats while the PET flakes sink; this physical separability is crucial in high-quality bottle-to-bottle recycling. Another new feature is the EcoFloat White option for light-sensitive products, which allows bottlers to switch from opaque HDPE or PET packaging to clear PET bottles.

With its WashOff labels, CCL also addresses the requirements of industrial washing processes in the reuse and refill sector. These pressure-sensitive labels can be removed in a lye bath without leaving any residue and thus support reusable glass and PET systems. In addition, the new EcoShear adhesive technology improves the recyclability of single-use glass bottles, as self-adhesive film labels are almost completely removable.

AN ADHESIVE FOR HIGH-SPEED LABELLING

Finally, the composition of supposedly minor components is also gaining in importance. With a new hot-melt adhesive that does not contain mineral oil, Henkel Adhesive Technologies offers a solution with a removal rate of up to 98 per cent in the recycling process. Residue is separated from the material flow together with the remains of the labels. The hot-melt adhesive solution is compatible for both paper and plastic labels and ensures smooth operation at high speeds of up to 40,000 bottles per hour while maintaining low processing temperatures of 110 to 140°C. This protects equipment, saves energy and increases operational reliability.

REPLACING LABELS WITH LASER MARKS

However, you can also do without labels: last year, Krones developed DecoBeam, a solution for marking PET and rPET bottles directly. Relevant information such as the product's net quantity, ingredients, best-before date and design elements are laser marked directly onto the bottles – saving material and making packaging easier to recycle. Two laser marking methods are available: CO_2 lasers result in a more white-ish colour, while fibre lasers produce black lettering. Logos, graphics and design elements can also be depicted alongside the text.

Krones also offers an alternative to classic labels for glass containers: INKpression transfers ink directly onto the containers themselves. What makes this application so special

THE WASHOFF LABELS CAN BE REMOVED FROM REUSABLE BOTTLES WITHOUT LEAVING ANY RESIDUE. IMAGE: CCL LABEL is that the ink is not applied through a classic printing process: the finished design is peeled off backing material and transferred onto the container as a whole.

BOOM IN CANS CONTINUES

The drinks can has been gaining in popularity for years. For example, sales of canned soft and energy drinks are currently experiencing a boom, particularly among younger target groups. In Europe, drinks cans also have a good recycling rate: over 76 per cent in 2023 and rising, according to figures from two European associations, namely Metal Packaging Europe (MPE) and European Aluminium (EA). Deposit systems have a

TECHNOMELT EM 335 RE CONTAINS NO MINERAL OIL, IS ALMOST COMPLETELY REMOVABLE IN THE RECYCLING PROCESS AND IS PETCYCLE-APPROVED. IMAGE: HENKEL

THE DEMAND FOR BEVERAGES IN CANS IS INCREASING. IMAGE: COCA-COLA / ULI DECK

significant effect here: countries with deposit-return systems achieve recycling rates of up to 90 per cent.

Many beverage manufacturers are currently expanding their range of cans. This year, for example, Coca-Cola Europacific Partners Germany (CCEP DE) is investing in a new canning line at its Halle location, which is expected to go into operation in the summer of 2026, when it will supplement the two existing bottling lines for non-carbonated beverages in PET bottles.

MORE ECO-FRIENDLY THAN THEIR REPUTATION WOULD HAVE YOU BELIEVE: DRINKS CARTONS. IMAGE: FKN

With this multi-million investment, Coca-Cola is responding to an increased demand: last year, sales of canned beverages increased by around 12 per cent compared to the previous year on the German market alone.

DRINKS CARTONS WITH A GOOD LCA

When it comes to drinks cartons, opinions often differ despite the fact that this form of packaging combines state-of-the-art technology: it is lightweight, opaque, recyclable and around three quarters of its material consists of cardboard fibre – supplemented by barriers that ensure the product is protected and help extend shelf lives. According to the German Association of Manufacturers of Carton Packaging for Liquid Foods (Fachverband Kartonverpackung für flüssige Nahrungsmittel e.V., FKN), when it comes to recycling, the industry is more advanced than many believe; the drinks carton has long been part of a functioning cycle, thanks to association companies Tetra Pak, SIG Combibloc and Elopak as well as the Palurec recycling plant at Knapsack Chemical Park. In Germany, around 36,000 tonnes of plastic and aluminium from drinks cartons are thus recycled every year. However, this is still not enough to meet the legally required quotas, and thus, according to current figures from the Central Agency Packaging Register (Zentrale Stelle Verpackungsregister, ZSVR), Germany failed to meet the recycling quota for the third time in a row in 2024.

TETHERED CAPS UNPOPULAR

As a study by the Nuremberg Institute for Market Decisions (NIM) shows, a majority of consumers find tethered caps impractical. Since mid-2024, single-use beverage packaging must be fitted with these tops, which remain attached to the packaging after opening. The aim is to reduce plastic waste and facilitate recycling. However, two thirds of respondents criticised the cumbersome handling – especially when drinking and pouring.

Numerous international exhibitors will demonstrate how to package beverages safely, appealingly and sustainably at interpack in Düsseldorf from 7 to 13 May 2026. Further information on the trade fair is available at www.interpack.de.

Packaging Review

"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.
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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.
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- 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.
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