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Eco-sustainable food packaging: Biobased multi-active films to mitigate migration of mineral oils and polyolefin oligomeric saturated hydrocarbons

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ABSTRACT

The migration of mineral oils from recycled paper and cardboard packaging to food has raised increasing concerns in recent years. In addition to mineral oil hydrocarbons (MOH), polyolefin oligomeric hydrocarbons (POH), a class of synthetic hydrocarbons derived from the polymerization of olefins such as ethylene and propylene, and often analytically mistaken for MOH, also pose a risk. POH can migrate from plastic materials into food, especially those made with polyolefins like polyethylene (PE) and polypropylene (PP), which are widely used in food packaging (films, trays, containers, etc.). Several solutions have been proposed, and others are still under development to address this issue. Currently, the most promising approach is the introduction of polymeric materials as a barrier to prevent the migration of these contaminants. The primary aim of this review is to provide an updated overview of the migration of MOH and POH from conventional packaging materials into foods, the parameters influencing this process, recent advances in innovative eco-sustainable barrier materials, and the testing methods used to measure their migration. Special attention is given to biopolymers, as they enhance the sustainability of paper and cardboard packaging while maintaining their recyclability.

1. Introduction

The global food packaging industry is currently undergoing a critical transformation, driven by environmental concerns and regulatory pressures aimed at reducing plastic waste and promoting circular economy principles. Conventional petroleum-based polymers, such as polyethylene (PE) and polypropylene (PP), have long been favored for their excellent mechanical and barrier properties. However, they are non-biodegradable, and only a small fraction (less than 10%) is effectively recycled. Improper disposal of these materials contributes to the accumulation of plastic debris in terrestrial and marine ecosystems, leading to the formation of microplastics detected in water, soil, and even human tissues, raising concerns about potential long-term impacts on health (Zhang & Sablani, 2021).

As a more sustainable alternative, paper- and board-based packaging, particularly that made from recycled fibers, has gained increasing attention as an eco-friendly option. Its use supports resource conservation and waste reduction. However, recycled fibers may introduce a complex mixture of chemical contaminants. While mineral oil hydrocarbons (MOH) are the most frequently discussed, recycled paper and board often contain other substances of toxicological concern, such as bisphenol A (BPA, used in thermal papers and epoxy resins), diisopropylnaphthalenes (DiPNs, solvent residues from carbonless copy paper), benzophenones (photo-initiators from UV-cured inks), bis(2-ethylhexyl) phthalate (DEHP, a plasticizer often found in adhesives), and alkylphenols ethoxylates (surfactants used in paper processing) (Suciu et al., 2013). Among these, MOH, derived mainly from petroleum-based inks and printing residues, remain a primary focus due to their high migration potential and widespread presence in the recycled stream.

MOH comprise two main fractions: mineral oil saturated hydrocarbons (MOSH), including linear, branched, and cyclic alkanes, and mineral oil aromatic hydrocarbons (MOAH), consisting of alkylated aromatic compounds with varying ring numbers (Bratinova et al., 2023). Although MOSH are generally of lower toxicological concern, MOAH species with three or more aromatic rings (≥3 R) and limited alkyl substitution have been associated with potential genotoxic and carcinogenic effects (EFSA, 2023).

In parallel, polyolefin oligomeric hydrocarbons (POH), including polyolefin oligomeric saturated hydrocarbons (POSH) and polyolefin oligomeric monounsaturated hydrocarbons (POMH), can migrate from plastic packaging materials such as PE and PP films, trays, and containers, posing an additional food safety issue (Biedermann & Grob,

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2015). Thus, both traditional plastics and recycled paper present inherent challenges. The former is due to their environmental persistence and contribution to microplastic pollution, and the latter is due to possible chemical migration from recycled sources.

To address these issues, biobased and biodegradable polymers have emerged as promising candidates for sustainable packaging applications. Derived from renewable resources, these bioplastics combine environmental benefits with the potential to reduce contamination risks. Their functionality can be further enhanced through multi-active systems, which integrate antimicrobial, antioxidant, and barrier properties to limit the migration of contaminants such as MOH and POH. This transition is supported by recent European policy frameworks, including the EU Green Deal, the Circular Economy Action Plan, and the Single-Use Plastics Directive (EU 2019/904).

Furthermore, a landmark regulatory update, the Regulation (EU) 2025/40 on Packaging and Packaging Waste (PPWR), published in December 2024, is set to replace Directive 94/62/EC, with most provisions becoming legally binding on 12 August 2026. This regulatory momentum, characterized by increasingly stringent limits for MOAH, is creating an unprecedented industrial pressure to identify safe alternatives. Consequently, there is a rapid expansion of biobased multi-active concepts that must now prove their efficacy not only as sustainable options but also as technically robust functional barriers (material layers that reduce or prevent the migration of substances from packaging into food) against MOH migration. Within this context, the development of eco-sustainable multi-active biofilms (derived from renewable resources and compatible with recycling, with reduced environmental impact) represents a crucial step toward safe and circular food packaging solutions that align with both environmental protection and public health objectives.

Fig. 1 shows a conceptual representation of three food packaging material categories and their role in contaminant migration. Conventional plastic materials and recycled paper-based packaging are associated with POH and MOH migration, respectively, whereas biobased multi-active films are designed to mitigate contaminant transfer while improving environmental sustainability.

This review summarizes recent advances in biobased barrier materials and multi-active films designed to mitigate the migration of MOH and POH in food packaging. Special attention is placed on the synergy between biopolymers and multi-active systems as a strategic solution to enhance the sustainability and functional barrier properties of paper and cardboard. The scope of this review specifically covers: (i) recycled paper and board as the primary source of MOH; (ii) polyolefin-based packaging (PE and PP) as the source of POH; (iii) mitigation strategies through innovative material design; and (iv) current analytical and migration-testing methodologies. The strategic roadmap for managing these contaminants, including sources, analytical challenges, and mitigation strategies, is summarized in Table 1.

The scientific and regulatory understanding of MOH and POH has significantly evolved over the last three decades, transitioning from early observations in recycled paper to the sophisticated analytical and legislative frameworks of today (Fig. 2).

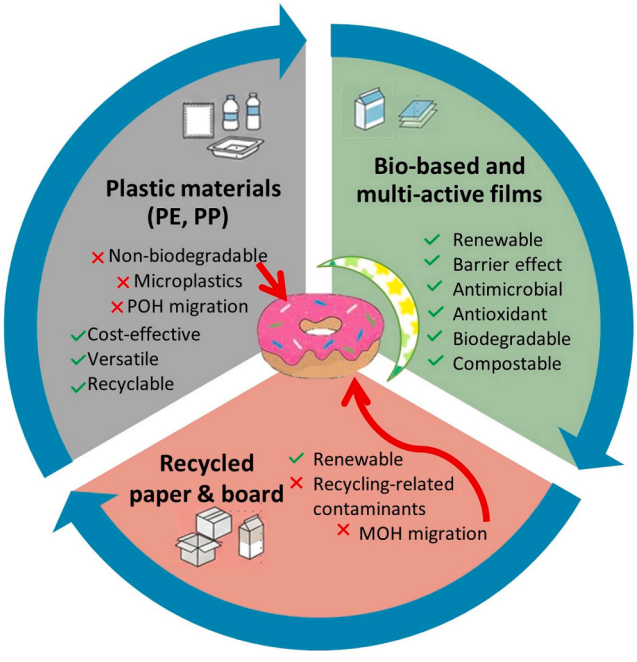

Fig. 1. Conceptual representation of three major food packaging material categories and their role in contaminant migration.

1.1. Methodology

A comprehensive literature search was conducted across the Scopus, Web of Science, and PubMed databases. The search focused on peer-reviewed articles, book chapters, and conference proceedings published within a time window from 2014 to 2026. The final search was performed on January 5th, 2026. Search terms included combinations of keywords such as "mineral oil hydrocarbons", "MOSH/MOAH", "polyolefin oligomers", "POH", "POSH/POHM", "biobased coatings", "functional barriers", and "food contact materials". Only studies published in English were included. After removing duplicates and screening for eligibility based on the presence of experimental migration data, a total of 87 studies were included in this review.

Data were extracted from the selected studies to identify the most relevant parameters for barrier performance. Due to the high heterogeneity of the experimental setups identified in the literature (e.g., different temperatures, storage times, and food simulants), a formal meta-analysis or mathematical normalization was not feasible. A comparative approach was used to synthesize the results. The synthesis

Table 1
Strategic roadmap for MOH and POH management in food packaging: from contamination sources and migration mechanisms to analytical challenges and bio-based mitigation strategies.

Key aspects	Sub-aspects	Technical features and current challenges
Sources	MOH	Recycled paper/board (offset inks, mineral oil-based additives), printing solvents, and machinery lubricants
	POH	Low molecular weight oligomers from PE and PP (films, trays, heat-seal layers)
Migration mechanisms	Gas phase	Evaporation-condensation of volatile fractions (<*n*-C_{24}) from packaging through the headspace
	Direct contact	Diffusion-driven transfer of heavier fractions (>*n*-C_{24}); accelerated by high-fat food and thermal treatments (e.g., microwave)
Analytical challenges	Co-elution	Overlap of POSH/POH humps with MOH fractions in GC-FID
	Methodology	Necessity of pre-separation (LC-GC-FID) or advanced characterization (GC×GC) to differentiate mineral oils from synthetic oligomers
Migration and barriers	Biobased barriers	Chitosan, starch, and cellulose derivatives provide high crystalline paths against non-polar migrants
	Multi-active systems	Integration of antioxidants/scavengers to inhibit oxidative degradation and adsorption of volatile hydrocarbons
Current gaps	Harmonization	Finalization of the EU 2025/40 Regulation limits
	Scalability	Industrial application of biocoatings and their resistance to high-humidity storage conditions

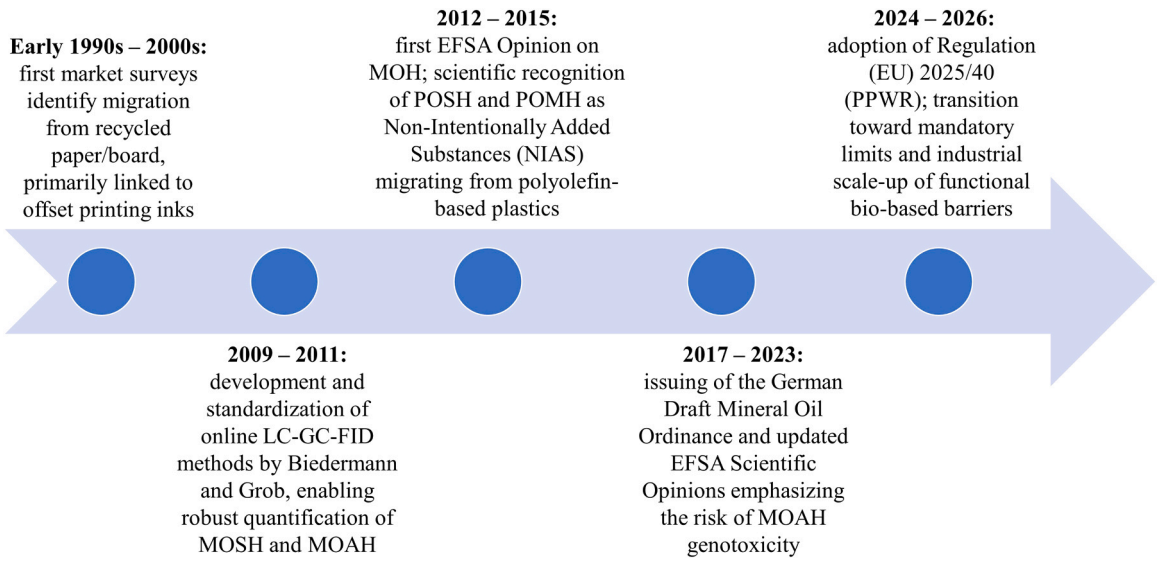

Fig. 2. Historical and regulatory evolution of MOH and POH in food packaging: from the early identification of migration from recycled fibers to the implementation of Regulation (EU) 2025/40.

focused on identifying performance trends and correlating the reported barrier efficiency with the specific testing methodology, thereby providing a critical overview of the current state-of-the-art despite the lack of standardized testing protocols.

2. Eco-sustainable packaging materials

In the transition toward a circular economy, the terms "ecological" (eco) and "sustainable" are frequently used, yet they represent distinct conceptual frameworks within packaging science. According to the holistic definition proposed by Dörnyei et al. (2023), sustainable food packaging is characterized by a "triple-bottom-line" approach that balances environmental, social, and economic factors. It must ensure food safety and quality, minimize environmental impact (through biobased origins or circularity), and be economically viable. Conversely, eco-friendliness (or being "eco") is a specific subset focusing on environmental metrics, such as biodegradability or carbon footprint. Therefore, eco-sustainable packaging integrates these ecological benefits with high functional performance to achieve a net positive impact on the entire food-packaging-consumer chain (Díaz-Montes & Castro-Muñoz, 2021; Dörnyei et al., 2023).

New packaging materials derived from renewable natural sources have been extensively characterized and classified as natural, synthetic, or modified natural polymers. Recent innovations include mono- and multilayer structures that maintain biodegradability and suitability for food contact. Ideally, biobased sustainable packaging should be derived from agricultural and food industry byproducts, avoiding competition with primary food production while promoting resource efficiency and waste valorization (Reichert et al., 2020). Incorporating plant-based food waste and byproducts into these matrices further aligns with sustainability goals by improving mechanical properties and reducing reliance on virgin materials (Zhang & Sablani, 2021).

These materials can enhance the quality of various food products, including fresh, frozen, and shelf-stable dry foods. By slowing microbial growth, reducing lipid oxidation, and minimizing moisture loss, they effectively extend shelf-life and maintain organoleptic properties. Additionally, in the context of dry foods stored in recycled paperboard, these biopolymers act as essential functional barriers against the migration of volatile contaminants. These materials can also serve as carriers for functional additives such as antimicrobials and antioxidants, offering customized protection based on the specific degradation pathways of the food matrix (Dehghani et al., 2018; Díaz-Montes & Castro-Muñoz, 2021; Kumar et al., 2022).

While often used interchangeably, films and coatings have different applications: films are self-standing laminates applied around a product or placed between components of a composite food, whereas coatings are thin layers of biopolymer-based material formed directly onto the food or packaging surface (Falguera et al., 2011; Peressini et al., 2003). Coatings are typically applied in liquid form through methods such as spraying, brushing, or dipping, and then dried. However, not all application methods are universally suitable for every product, highlighting the need for customized formulations tailored to specific foods (Ahvenainen, 2003). The functionality of films and coatings heavily relies on their composition and structure, making it crucial to evaluate their mechanical and barrier performance under real environmental conditions (Mohamed et al., 2020).

2.1. *Biodegradable polymer films applied to biobased food packaging*

Most biobased films currently available for the food industry exhibit limited functional properties, which can be improved by applying coating layers. There are various techniques for depositing solutions or suspensions onto films, such as electrospray, flexography, and simple casting, followed by drying or polymerization induced by heat, UV radiation, or other methods (Kurek & Debeaufort, 2016). A major challenge in developing biodegradable coatings for flexible multilayer packaging is the need to blend immiscible materials without the use of synthetic additives or compatibilizers (Debeaufort et al., 2025).

Debeaufort et al. (2022) improved the barrier and antioxidant properties of polylactic acid (PLA, a biodegradable, compostable polymer approved for food contact by both the Food and Drug Administration -FDA- and EU regulations) by coating it with a cross-linked gelatin suspension containing phenolic compounds (tannic and gallic acid). This treatment preserved the mechanical integrity of PLA while reducing oxygen transfer by up to 600-fold, making it suitable for oxidation-sensitive foods.

Similarly, Rocca-Smith et al. (2019) developed PLA-wheat gluten-PLA multilayer films with enhanced oxygen barrier performance. The combination of PLA and gluten acted as complementary limiting factors to mass transfer. The gluten layer decreased the transfer rate of oxygen, while PLA reduced water vapor transfer due to its hydrophobic nature.

Chitosan coatings have also been shown to significantly reduce oxygen permeability by 2–5 times (Hosseini et al., 2016), and by up to 50

times when combined with silicon oxide (SiOx) layers (Ren et al., 2020). These findings support the idea that biodegradable packaging is a promising pathway towards sustainable materials (Debeaufort et al., 2025).

2.2. Strengths and limitations compared to conventional packaging materials

Briassoulis & Giannoulis, 2018 compared the functionality of selected commercial biodegradable films (Mater-Bi, PLA, Ecovio) with conventional non-biodegradable plastics such as biaxially oriented polypropylene (BOPP), the most widely used film in food packaging. They reported higher water vapor permeability and differences in mechanical properties (tensile strength and puncture resistance) among biobased materials, while emphasizing that overall functionality remained satisfactory for targeted food applications. Similarly, Calva-Estrada et al. (2019) concluded that protein-based films, though still inferior to synthetic polymers in terms of absolute barrier performance, show potential for improvement through nanocomposite approaches (Hajizadeh et al., 2020) or incorporation of natural antimicrobial and antioxidant agents to extend food shelf-life (Dehghani et al., 2018).

Recent reviews (Galus et al., 2020; Reichert et al., 2020; Tyagi et al., 2021) confirm that the increasing relevance of eco-sustainable barrier materials, covering innovations in biobased coatings and industrial processing techniques. However, biopolymers still face technical and economic hurdles, including limited scalability, delamination, poor heat-sealability, and the potential migration of coating components into food. While biobased films are often perceived as inherently safe, several studies have highlighted the potential migration of non-intentionally added substances (NIAS), residual monomers, and high concentrations of plasticizers (e.g., glycerol or polyols) required to improve film flexibility (Lestido-Cardama et al., 2025). In this context, the development of multi-active systems requires a rigorous safety assessment to ensure that the active compounds and their possible degradation products do not compromise food safety.

Compared with synthetic plastics, biobased polymers are often brittle, thermally unstable, and less effective barriers against water vapor and oxygen (Agarwal et al., 2023; Ferreira-Filipe et al., 2021; Mendes & Pedersen, 2021; Rosenboom et al., 2022; Russell, 2014). To overcome these limitations, current strategies include the incorporation of nanoparticles, polymer blending, and surface modification (Debeaufort et al., 2025).

2.3. Industrial application and evolutionary trends

Over the past decade, the industrial adoption of biopolymers in food packaging has undergone a significant evolution, transitioning from niche laboratory solutions to structural components of complex packaging systems.

Initially, industrial interest was primarily focused on identifying and classifying polymers extracted from biomass, such as polysaccharides (starch, cellulose, chitosan) and proteins, or those synthesized from bio-derived monomers, including PLA and polycaprolactones (PCL) (Fabra et al., 2014). Early applications were mostly limited to edible coatings for fresh produce. As research progressed, the industry leveraged the barrier and mechanical properties of these materials to move beyond simple coatings, exploring them as viable alternatives to conventional petroleum-based plastics (e.g., PE, PP, and polyethylene terephthalate - PET) in films and rigid containers, driven by the urgent need to reduce the carbon footprint of the sector (Grujić et al., 2017).

More recently, industrial implementation has shifted towards active and technologically advanced biopolymer systems. Beyond standard applications in the dairy and meat sectors, current industrial efforts are concentrating on incorporating nanoparticles and bioactive compounds within natural matrices (such as soy protein isolate or chitosan) to improve mechanical strength and water resistance, historically the primary challenges for biobased materials (Gupta et al., 2022). Currently, PLA, polyhydroxyalkanoates (PHAs), and starch-based blends are the most commercially mature solutions for producing single-use cutlery, bags, and barrier films, with emerging trends exploring advanced manufacturing techniques such as 3D printing for customized food contact applications (Gupta et al., 2022).

3. MOH and POH contaminants deriving from packaging

3.1. Definition and sources of MOH and POH

MOH refers to a complex group of hydrocarbons containing approximately 10–50 carbon atoms. These compounds primarily come from petroleum and its byproducts, but can also be produced synthetically from coal, natural gas, and biomass. MOH are conventionally divided into two main groups, each with numerous isomers: saturated hydrocarbons (MOSH) and aromatic hydrocarbons (MOAH) (Fig. 3). MOSH consists of linear and branched aliphatic hydrocarbons (alkanes and isoalkanes, also known as paraffins and isoparaffins), as well as cyclic compounds (cycloalkanes or naphthenes), potentially alkylated.

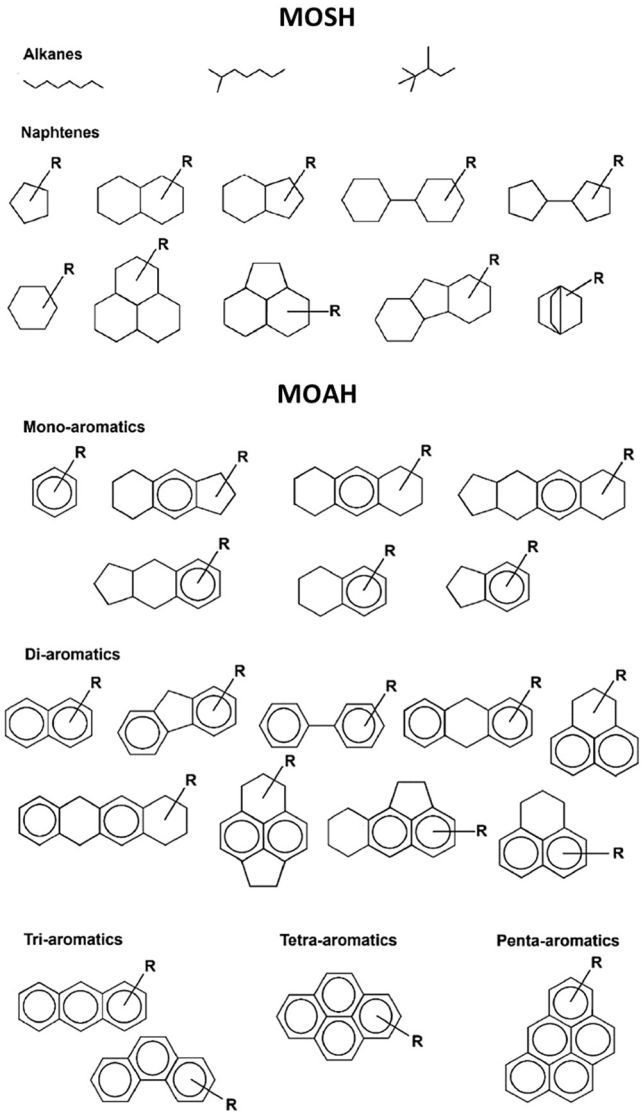

Fig. 3. Representative chemical structures of Mineral Oil Saturated Hydrocarbons (MOSH) and Mineral Oil Aromatic Hydrocarbons (MOAH). Adapted from EFSA, 2012.

On the other hand, MOAH are composed of hydrocarbons containing one or more benzene rings, mainly alkylated (EFSA, 2012; Bratinova et al., 2023).

Similarly, POH, mainly POSH, consist of short-chain oligomers (2–20 monomer units, Fig. 4) formed as byproducts during the polymerization of polyolefins. They are not intentionally added to the formulation and are thus classified as Non-Intentionally Added Substances (NIAS) (Busico et al., 2005; Greenwood, 2006). In addition to POSH, POMH may also be generated during polymerization or thermal degradation of polyolefins. POMH contain a single double bond per molecule and are generally more volatile and chemically reactive than their saturated counterparts. They usually account for less than 10% of the total POH; due to their low abundance and instability, they are rarely quantified separately in migration studies. Nonetheless, their presence can indirectly contribute to contamination through oxidation or conversion into aldehydes and carboxylic acids during storage or thermal processing (Biedermann-Brem & Grob, 2011).

The composition of the oligomeric fraction depends on the monomer type, catalyst system, and the specific polymerization conditions (Busico et al., 2005; Greenwood, 2006). Because of their structural similarity, POSH and POMH may be analytically misidentified as MOSH (Biedermann-Brem et al., 2011). To clarify their differences, Table 2 summarizes the key chemical characteristics, primary sources, and toxicological profiles of MOSH, MOAH, and POH.

3.2. MOH from recycled paper and cardboard

3.2.1. Toxicological relevance

The risk assessment of MOH in food has been a central focus of the European Food Safety Authority (EFSA) for over a decade, primarily due to the potential health implications of its two main fractions: MOSH and MOAH. In its 2012 opinion, the EFSA Panel on Contaminants in the Food Chain (CONTAM) identified numerous sources of MOH in food, distinguishing between intentional uses and environmental or packaging-related contamination. Among food contact materials (FCM), recycled paper and board packaging were identified as the most critical sources, contributing significantly to dietary exposure, especially when used without an effective internal functional barrier. This is primarily due to the presence of MOH-based printing inks used in newspapers that enter the recycling stream.

Based on occurrence data, EFSA estimated that toddlers and children are the age groups most significantly exposed to MOH. Specifically, MOSH exposure for these vulnerable groups reached levels up to 0.04 mg/kg body weight (b.w.) per day from bakery products, 0.07 mg/kg b.w. per day from breakfast cereals, and 0.11 mg/kg b.w. per day from rice (EFSA, 2012). Beyond recycled fibers, the CONTAM Panel highlighted a wide array of other FCM-related sources, including additives in plastics (e.g., internal lubricants used in the manufacture of polystyrene and polyolefins), adhesives, coatings, jute or sisal bags treated with batching oils, and wax coatings applied directly to certain

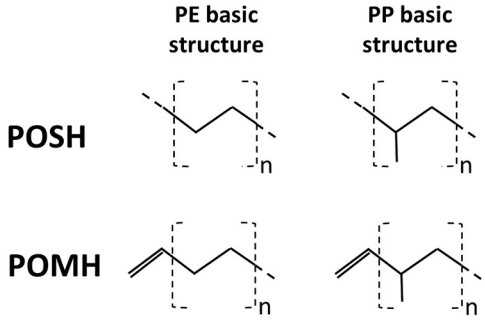

Fig. 4. Representative chemical structures of Polyolefin Oligomeric Saturated Hydrocarbons (POSH) belonging to polyethylene (PE) and polypropylene (PP).

Table 2
Similarities and differences between MOSH, MOAH, and POH in terms of chemical structure, sources, migration pathways, and toxicological relevance.

	MOSH (Mineral oil saturated hydrocarbons)	MOAH (Mineral oil aromatic hydrocarbons)	POH (Polyolefin oligomeric hydrocarbons)
Chemical structure	Saturated hydrocarbons (≈C_{10}-C_{50}): linear, branched, and cyclic compounds with possible side-chain alkylation.	Aromatic hydrocarbons (≈C_{10}-C_{50}): one or more benzene rings, predominantly alkylated.	POSH - Polyolefin oligomeric saturated hydrocarbons, short-chain oligomers (≈C_{20} and above), mainly branched, sometimes cyclic (with side chains); generally lower proportion of cyclic alkanes than MOSH. POMH - Polyolefin oligomeric monounsaturated hydrocarbons: short-chain oligomers, characterized by the presence of a single double bond.
Primary source	Petroleum-derived products (i.e., printing inks, lubricants, adhesives, waxes).	Petroleum-derived products (i.e., printing inks, lubricants, adhesives).	Byproducts of polyolefin polymerization (i.e., PE, PP) or deliberately added as process adjuvants.
Pathways of migration into food	Transfer from packaging, environmental contamination, or food/feed additives.	Transfer from packaging, environmental contamination, or food/feed additives.	Migration from polyolefin-based plastic packaging (i.e., films, containers, coatings).
Toxicological relevance	Bioaccumulative; potential adverse health effects under long-term exposure.	Potentially genotoxic and carcinogenic (especially low-alkylated compounds with ≥3 aromatic rings).	Bioaccumulative; potential health risk, though limited toxicological data are available.

foods (e.g., fruits or confectionery) (EFSA, 2012). The 2012 assessment further highlighted that while MOSH can accumulate in human tissues (notably the liver and lymphoid system), the MOAH fraction, particularly compounds with 3 or more aromatic rings, poses a more severe threat due to their potential genotoxicity and carcinogenicity (EFSA, 2012). This multifaceted contamination landscape, recently reaffirmed in the 2023 EFSA Scientific Opinion (EFSA, 2023), underscores that mitigating migration through the development of effective internal functional barriers is not merely a technical challenge but a fundamental requirement for food safety.

3.2.2. Legislations

Despite increasing awareness and continued efforts by competent authorities to implement restrictive measures, harmonized EU limits for MOH migration are still in a transitional phase, leading to a complex regulatory landscape (Table 3). In the European Union, the overarching Framework Regulation (EC) No. 1935/2004 and the Good Manufacturing Practice (GMP) Regulation (EC) No. 2023/2006 set the general safety principles for all FCM. While specific measures exist for plastics under Reg. EU 10/2011, harmonized regulations for paper, board, and glass are still pending, though they remain high-priority areas for future legislation. Similarly, in the United States, the FDA

Table 3
Recent regulatory measures and guidance on MOH and packaging.

Authority / Country	Year	Measure / Guidance	Scope	Limits / Key provisions
EU (Recommendation 2017/84)	2017	Systematic monitoring	Food and packaging	Encourages monitoring of MOH in food and packaging materials
German Federal Ministry of Food and Agriculture (BMEL)	2020	Functional barrier requirement	Packaging	Mandatory use of a functional barrier unless migration < 0.5 mg MOAH/kg food or < 0.15 mg/kg in food simulants
France (AGEC Law 2020−105 and implementing decrees)	2020	Ink restrictions	Packaging	MOAH $> 0.1\%$ banned; MOAH (3–7 rings) > 1 ppm; MOSH $> 0.1\%$
EU (Guidance values)	2022	Indicative MOAH limits	Food	0.5 mg/kg (low-fat), 1 mg/kg (medium-fat), 2 mg/kg (high-fat food, oils/fats)
EFSA	2023	Scientific opinion	Food	No risk from MOSH; MOAH ≥ 3 rings remain of carcinogenic concern
EU Joint Research Centre (JRC)	2023	Technical guidance on sampling and analysis	Food and packaging	Harmonized analytical methodology for monitoring MOSH and MOAH.
Switzerland (Directive 84/500/EEC)	2024	Packaging restrictions	Packaging	Recycled paper not allowed in direct contact; unauthorized ink substances < 0.01 mg/kg
Draft EU Regulation (v7)	2025	Proposed harmonized EU-wide limits	Food	MOAH limits: $\leq 4\%$ fat ➔ 0.5 mg/kg; 4–50% fat ➔ 1.0 mg/kg, $> 50\%$ fat ➔ 2.0 mg/kg

regulates migrating substances as indirect food additives, requiring premarket approval only if migration exceeds levels of concern and the substance is not Generally Recognized as Safe (GRAS).

Within this context, the specific issue of MOH migration has been addressed through a combination of monitoring recommendations and targeted enforcement levels. The Commission Recommendation (EU) 2017/84 encouraged systematic monitoring of MOH in food and packaging across Member States. A pivotal shift occurred in May 2022, when the Standing Committee on Plants, Animals, Food and Feed (SCoPAFF) established harmonized action levels for MOAH (0.5–2.0 mg/kg, depending on food fat content), which currently serve as the primary reference for market enforcement.

Recently, EFSA (2023) reaffirmed that, while current MOSH exposure does not raise immediate health concerns, MOAH with ≥ 3 R remain a significant carcinogenic concern. Consequently, the draft EU Regulation (2025) proposes harmonized EU-wide MOAH limits based on fat content: ≤ 0.5 mg/kg for food with $\leq 4\%$ fat; ≤ 1.0 mg/kg for food with 4–50% fat, and ≤ 2.0 mg/kg for food with $> 50\%$ fat.

In the absence of full EU harmonization, several countries have implemented stricter national measures. Under the AGEC Law (2020–105) and subsequent decrees, France has prohibited the use of inks containing MOAH $> 0.1\%$, with a further restriction targeting MOAH with 3–7 rings effective from 2025. In 2020, Germany introduced the 22nd Amendment to the Consumer Goods Ordinance, which mandates the use of functional barriers for recycled paper and board packaging. Similarly, the Swiss Ordinance on Materials and Articles (SR 817.023.21) restricted the use of recycled paper in direct contact with food and limited unauthorized ink components (<0.01 mg/kg).

Hot-melt adhesives used in food packaging, which mainly consist of paraffinic waxes, hydrocarbon resins, and polyolefins, represent another critical contamination pathway. Hydrocarbon resins can release volatile hydrocarbons that migrate into dry foods and may be analytically misidentified as MOH from recycled cardboard (Lommatzsch et al., 2016). These materials must comply with Article 3 of the European Framework Regulation (EC) 1935/2004, ensuring they do not endanger human health, and must be produced in accordance with GMP.

The coexistence of diverse national measures alongside broader EU recommendations creates a complex and sometimes contradictory regulatory landscape for stakeholders. While the Framework Regulation (EC) No. 1935/2004 provides a horizontal safety basis, the lack of specific, harmonized vertical legislation for paper and board leads to significant challenges. On one hand, national initiatives drive innovation, pushing the industry towards adopting functional barriers and MOH-free inks. On the other hand, this lack of harmonization creates a fragmented internal market. This patchwork of regulations increases the analytical and compliance burden for food business operators, who must navigate differing limit values and methodological approaches.

However, the recent 2022 SCoPAFF guidance values and the 2025 Draft Regulation represent a significant step toward convergence. Currently, this transitional phase has made compliance more rigorous than before, requiring a safety-by-design approach where the most restrictive national limit often becomes the de facto target for products intended for the entire European market. Emerging EU-wide compliance frameworks for MOH and harmonized regulatory limits will increasingly influence material selection and barrier design. Future research should therefore align the development of biobased polymers with these evolving regulatory requirements to ensure both sustainability and legal compliance.

3.3. POH from polyolefin-based materials

3.3.1. Toxicological relevance

The toxicological assessment of POH has significantly evolved between the two EFSA opinions. In its initial assessment, the CONTAM Panel noted that POSH are structurally similar to MOSH (comprising branched and cyclic alkanes) and are often analytically indistinguishable from them using conventional LC-GC-FID methods. Due to this structural similarity and the lack of specific toxicological data, EFSA suggested, as a precautionary measure, that the toxicological considerations applied to MOSH should also be extended to POSH. Dietary exposure was already considered relevant due to the ubiquitous use of polyolefins in direct food contact (EFSA, 2012).

The recent 2023 Scientific Opinion provided further nuance. While POSH continue to be treated with similar concern to MOSH regarding their potential for tissue accumulation, EFSA highlighted that the chemical complexity of these oligomers requires more specific monitoring. Crucially, the 2023 Opinion addressed the potential presence of POAH (the aromatic fraction of polyolefin oligomers). Although POAH are generally present at much lower levels than MOAH found in recycled paper, their potential migration from certain plastic additives or adhesives cannot be ignored (EFSA, 2023).

Dietary exposure to POSH is often underestimated or hidden within the reported MOSH values. EFSA emphasized that migration from plastic packaging can be substantial, especially for fatty foods, where diffusion from polyolefins is kinetically favored. The Panel reiterated that since POSH and MOSH share similar metabolic pathways and accumulation patterns in the liver and spleen, their combined presence

in the diet contributes to the overall mineral oil-like hydrocarbon burden. This cumulative exposure is particularly critical for high-consumption groups, such as toddlers and children, as migration from plastic films and internal layers of multilayer boards (even when used as barriers) can significantly add to the background contamination from recycled fibers (EFSA, 2023).

3.3.2. Legislation

POH poses a significant regulatory challenge, as they are inherent byproducts of the polymerization process of polyolefins. According to Regulation (EU) No. 10/2011, POH are classified as NIAS. Since POH are not listed as authorized substances in Annex I of the Plastic Regulation, they lack a dedicated, harmonized Specific Migration Limit (SML). However, Article 19 of Regulation 10/2011 states that their presence must be assessed by the manufacturer in accordance with internationally recognized scientific principles of risk assessment. In practice, this requires a self-compliance approach in which the producer must demonstrate that any migrating oligomers do not exceed levels that could endanger human health, often relying on the threshold of toxicological concern (TTC) approach or the general safety principles of Regulation (EC) No. 1935/2004.

3.4. Sample preparation and analytical determination of MOH and POH

The reference analytical method for the quantification of MOSH and MOAH is the online high-performance liquid chromatography (HPLC) coupled to gas chromatography (GC) with flame ionization detection (FID) approach, developed by Biedermann et al. (2009) and officially endorsed by EFSA, 2023 and the Joint Research Center (JRC) (Bratinova et al., 2023). In this technique, a silica LC column separates polar interferences, including lipids, and enables MOSH/MOAH fractionation for subsequent GC analysis. FID is preferred as it provides a consistent response per unit mass for all hydrocarbons, avoiding calibration complexities encountered with mass spectrometry (MS). However, the limited selectivity of FID requires careful sample preparation, particularly for complex food matrices (Purcaro et al., 2016).

Comprehensive two-dimensional GC (GC × GC), coupled with FID and/or MS, serves as a powerful confirmatory tool for detailed characterization, source identification, and the differentiation of MOH from POSH fractions. Due to their structural resemblance, POSH and MOSH may frequently co-elute, forming humps of unresolved components in the chromatogram (Biedermann-Brem et al., 2012). While LC-GC-FID allows for rapid determination, it cannot distinguish POSH from MOSH when their molecular weight distributions overlap (Biedermann et al., 2009).

GC × GC-FID/MS further enhances MOSH characterization and allows the differentiation between non-alkylated and highly alkylated MOAH, as well as the identification of the number of aromatic rings. By employing a phenyl methyl polysiloxane column in the first dimension and a dimethyl polysiloxane column in the second dimension, Biedermann and Grob (2015) successfully differentiated MOSH from POSH and assessed the refinement levels of mineral oils. Although a complete chemical characterization is not always achievable due to the complexity of the mixture, the application of enrichment techniques can achieve detection limits below 0.5 mg/kg of total MOSH or MOAH (Purcaro et al., 2016).

For the determination of POSH in the presence of MOSH, combining LC pre-separation with GC × GC is considered the most effective strategy (Biedermann et al., 2015). Furthermore, Lommatzsch et al. (2015) proposed an advanced HPLC-HPLC-GC-FID system, featuring a silica gel column to separate MOSH/MOAH, followed by a silver-impregnated HPLC column to isolate POSH from POMH.

Extraction procedures vary depending on the sample matrix. For packaging materials, simple extraction using a hexane/ethanol mixture (1:1, *v/v*) (Lorenzini et al., 2010) or pressurized liquid extraction (PLE) (Moret et al., 2013) provides good recoveries. For polyolefin plastics (PE, PP), prolonged contact with hexane (typically overnight) is often required due to the low permeability of the polymer matrix. For food matrices, extraction must be matrix-specific (Hochegger et al., 2021; Purcaro et al., 2016). For dry foods (e.g., rice, pasta), a two-step sequential extraction is recommended: the sample is first treated with ethanol to induce matrix swelling; subsequently, the ethanol is separated, and the solid residue is re-extracted with hexane. The two solvent fractions are then combined, and water is added to trigger liquid-liquid partitioning, forcing the migration of MOH/POH into the upper hexane layer for subsequent analysis (Biedermann-Brem & Grob, 2011). For fatty foods, saponification or microwave-assisted saponification (MAS) improves extraction efficiency (Moret et al., 2016). Subsequent sample clean-up steps, such as the epoxidation of olefins or *n*-alkane removal on activated alumina, are essential to ensure accurate quantification (EFSA, 2023; Purcaro et al., 2016). Despite methodological advances, harmonized interlaboratory validation remains limited, with standardized protocols currently available only for vegetable oils and infant formula.

3.5. Mechanism of migration

The migration of MOH and POH is a dynamic mass transfer process governed by the physico-chemical properties of the migrant, the packaging matrix, and the food (Helmroth et al., 2002; Mousavi et al., 1998). In homogeneous polymeric materials, such as plastic films, this process follows Fick's second law of diffusion (Fig. 5), where the diffusion and the partition coefficients determine the rate and equilibrium of the transfer (Miltz et al., 1997; Simoneau, 2008; Silva et al., 2007).

While POSH migration levels typically range between 0.1 and 5.0 mg/kg (Biedermann-Brem et al., 2012; Zhang et al., 2019), regional variability in polymer formulation can further influence these values (Srbinovska et al., 2022). The extent of POSH migration is strongly influenced by the polymer's microstructure characteristics, such as chain branching and crystallinity, alongside processing conditions. During thermal processing and recycling, chain scission and additive degradation generate low-molecular-weight oligomers and neoformed substances that are highly mobile within the polymer matrix. In addition, residual catalyst systems and polymerization byproducts contribute to a pool of low-molecular-weight species that are particularly prone to migration (Palkopoulou et al., 2016).

Several studies (Conchione et al., 2020; Biedermann-Brem et al., 2012; Zhang et al., 2019) have demonstrated that temperature, contact time, and food properties (e.g., fat content) significantly affect migration kinetics. Moreover, although most research focuses on POSH, POMH also may diffuse through the matrix, especially under high-temperature or oxidative conditions. Their unsaturated nature increases their chemical reactivity, potentially leading to the formation of oxygenated byproducts that can alter the organoleptic profile of the food (Biedermann et al., 2013).

By contrast, porous materials, such as recycled paper and board, exhibit a multiphase mass transfer mechanism, combining solid-phase diffusion through the cellulose fibers and gas-phase diffusion through the interstitial pores (Boccacci Mariani et al., 1999). Due to the high volatility of low-molecular-weight MOH fractions (up to C_{24}), the gas-phase transport often dominates the migration process, especially in dry food applications.

To better understand these complex dynamics, the following case studies illustrate the impact of key parameters, including food affinity, temperature, storage duration, and the performance of functional barriers.

3.5.1. The role of food composition

The chemical affinity between the migrant and the food matrix is a primary driver for the accumulation of MOH and POH.

In dry foods with high surface-area-to-volume ratio and low-fat content, such as rice or couscous, migration is dominated by the gas-phase transfer of volatile hydrocarbons (up to C_{24}). Under these

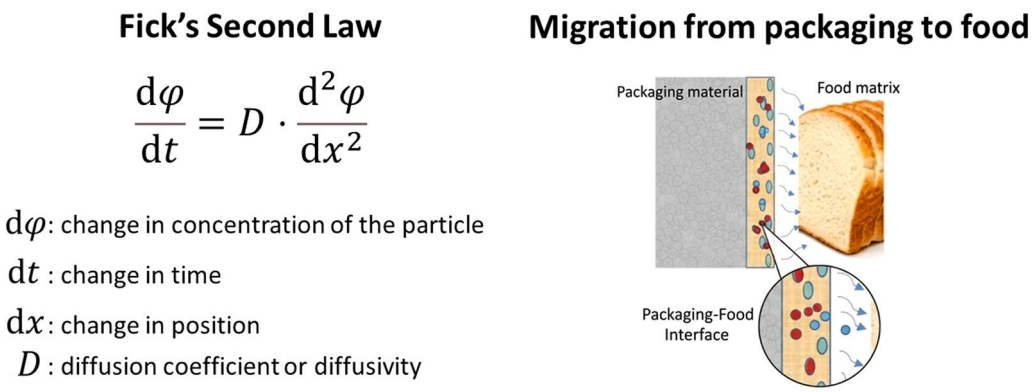

Fig. 5. Schematic representation of diffusion-driven chemical migration from packaging materials into food. Migration occurs from regions of higher to lower concentration across the packaging–food interface and is governed, in homogeneous polymeric materials, by Fick's second law of diffusion, which describes the time-dependent evolution of the migrant concentration within the packaging matrix.

conditions, up to 70% of the MOSH content in a recycled paperboard box can be transferred to the food within a few months, even in the absence of direct contact (Biedermann & Grob, 2010; Lorenzini et al., 2010). Black tea has demonstrated particularly high vulnerability to this phenomenon, with reported contamination levels reaching 102.2 mg/kg for MOSH and 7.9 mg/kg for MOAH (Moret et al., 2012).

For lipid-rich products, such as egg pasta or baked goods, the fat phase acts as a potent absorptive sink, promoting the migration of heavier, less volatile fractions (> C_{24}) that would otherwise remain stationary in dry matrices. In these cases, the total hydrocarbon concentration can triple by the end of the product's shelf life (Barp et al., 2015b; Moret et al., 2012; Vollmer et al., 2011).

3.5.2. *Temperature and shelf -life*

Temperature significantly accelerates migration kinetics, as diffusion coefficients typically rise exponentially with thermal energy (Alamri et al., 2021). Studies on breakfast cereals have shown that migration is a persistent and cumulative process. At standard storage temperatures (20°C), the concentration of MOH in food follows a non-linear increase, often tripling between the 3rd and 12th months of storage and frequently exceeding the 2.0 mg/kg threshold only in the latter half of the shelf-life (Barp et al., 2015a,b; Biedermann et al., 2013; Vollmer et al., 2011).

Exposure to 40°C (simulating transport or improper warehouse storage) can trigger a migration surge, transferring in just 21 days the quantity of contaminants normally released over six months under ambient conditions (Vollmer et al., 2011). Active heating further intensifies this phenomenon: microwave treatment of ready-to-eat soups has been shown to increase POSH transfer from 0.1 to 6.2 mg/kg (Conchione et al., 2020).

Overall, temperature plays a critical role in accelerating MOH and POH migration. Elevated yet realistic use conditions, such as prolonged storage, high-temperature transport, and microwave heating, significantly increase contaminant transfer compared to standard conditions. Future research should prioritize strategies for POH mitigation by systematically investigating the influence of polymer type, crystallinity, and processing conditions on oligomer formation and migration, while incorporating realistic scenarios, such as hot-fill and microwave applications, to improve the accuracy of exposure assessments.

3.5.3. *Efficiency of internal liners*

The efficiency of internal liners has been extensively studied. PE inner bags can absorb approximately 40% of hydrocarbons, acting as a temporary buffer that delays diffusion. However, their barrier efficiency decreases over long periods of storage and at high temperatures, turning the liner into a new source of POSH contamination (Barp et al., 2015a, b).

Aluminium foil and PET laminates provide the highest efficiency, effectively blocking migration below detection limits. In contrast, vapor-deposited aluminium (metalized films) and acrylate-coated PP reduce migration but do not completely prevent it beyond 0.5 mg/kg (Biedermann et al., 2013; Vollmer et al., 2011).

In addition to MOH and POH, resin oligomeric saturated hydrocarbons (ROSH) and resin oligomeric aromatic hydrocarbons (ROAH) from polymer coatings and hot-melt adhesives show similar diffusion behavior to MOH, making it more challenging to differentiate analytically and assess the risk (Barp et al., 2015b).

3.6. *Testing methods for barrier performance*

Testing methods for evaluating the protective capacity of packaging materials are generally classified into three categories: migration, permeation, and lag-time tests (Diehl & Welle, 2015). To avoid technical ambiguity, it is essential to distinguish between the underlying physical mechanisms. The permeation mechanism refers to the steady-state flux of a permeant through the barrier material (Fengler & Gruber, 2020). It is an intrinsic property of the material interface and the polymer bulk, often expressed through the permeability coefficient.

In contrast, the migration mechanism describes a non-steady-state mass transfer from a finite reservoir (the packaging) into a specific sink (food or simulant). Unlike permeation, migration is governed by both diffusion and partition coefficients; the latter reflects the chemical affinity between the migrant and the food matrix (Diehl & Welle, 2015).

In migration testing, food simulants are generally preferred over real foods to minimize analytical interferences and improve reproducibility. An effective simulant should mimic the polarity and lipophilicity of the target food while facilitating extraction and analysis. Within the European regulatory framework, Regulation (EU) No. 10/2011 serves as the primary reference. Specifically, it identifies poly(2,6-diphenyl-*p*-phenylene oxide), commercially known as Tenax®, as the official simulant E for dry foods. Technical implementation for paper-based materials often follows the DIN SPEC 5010:2018–05 standard, which recommends testing at 60°C to simulate long-term storage and ensure interlaboratory comparability.

3.6.1. *Experimental configurations*

Various experimental setups have been developed to measure the barrier efficiency, depending on whether they quantify intrinsic permeation or practical migration.

3.6.1.1. Migration-based setups. Glass-cell methods typically involve a robust stainless steel or glass apparatus where the barrier film is clamped between two chambers. The donor side contains a contaminated material (e.g., recycled board), while the receiver side is filled with a food simulant (e.g., Tenax® or a liquid simulant). This setup allows for strict

control over the contact area and pressure, effectively simulating long-term migration under standardized conditions (Guazzotti et al., 2015; Paul et al., 2017).

Similarly, the "cup test" method allows for the evaluation of gas-phase migration through coated substrates into adsorbents like powdered sugar or Tenax®. This configuration is particularly useful for measuring the reduction factor provided by a coating or internal liner, offering a direct assessment of how effectively the barrier inhibits the transfer of volatile hydrocarbons (Laine et al., 2016).

3.6.1.2. Permeation-based and rapid screening setup. The spiked donor/absorber setup uses a simplified, high-throughput configuration optimized for gas-phase transfer. In this method, a filter paper is spiked with a specific mixture of surrogate hydrocarbons to evaluate the barrier resistance against volatile migrants (Fiselier & Grob, 2012).

Similarly, dynamic acceptor systems (Ewender & Welle, 2014) employ a continuous gas stream that sweep volatile hydrocarbons toward an analytical trap allowing for real-time monitoring of permeation kinetics. Additionally, gravimetric permeation methods can be used to measure the mass loss (evaporation rate) of volatile *n*-alkanes (C_{16}–C_{24}) through a barrier film, providing a straightforward assessment of permeability (Gaudreault et al., 2013).

3.6.1.3. Lag-time experiments. These experiments are designed to calculate diffusion and partition coefficients independently of concentration or film thickness. By measuring the time required for a migrant to traverse the barrier and reach a steady-state flux, researchers can derive fundamental parameters needed to bridge experimental permeation data with migration predictions in real food systems (Diehl & Welle, 2015).

3.6.2. Correlation and modeling

Mathematical modeling serves as a powerful tool to correlate distinct transport mechanisms, enabling researchers to predict MOH levels in foods and extrapolate long-term migration behavior from short-term permeation or lag-time data (Fengler & Gruber, 2020). For instance, Laine et al. (2016) demonstrated through the "cup test" and subsequent modeling that fiber sorption within the paperboard matrix can significantly retard migration beyond the rates predicted by simplified Fickian diffusion models.

However, accurate comparison and validation require a comprehensive understanding of critical parameters, such as film thickness and thermal history. Although accelerated testing can reduce experimental time, elevated temperatures may distort migration behavior by promoting the migration of higher-molecular-weight hydrocarbons that would not significantly migrate under normal storage conditions (Fengler & Gruber, 2020). Therefore, the integrated use of model compounds (surrogates) and diffusion modeling remains essential to translate laboratory-scale data into realistic predictions of actual packaging migration performance under real-world supply chain conditions.

4. Biobased materials as functional barriers against MOH and POH migration

The development of biobased functional barriers represents a promising strategy to mitigate the migration of MOH and POH from recycled and plastic packaging into food. These materials can be implemented as surface coatings, inner liners, laminates, or multilayer systems, providing both mechanical protection and chemical safety while maintaining biodegradability and sustainability (Chen et al., 2023). Depending on their composition and architecture, biobased functional barriers operate through three main mechanisms: i) diffusion control, achieved by forming dense, compact, or cross-linked polymer networks that reduce molecular mobility; ii) adsorption or absorption, whereby hydrocarbons are partially retained within the barrier matrix; and iii) reactive scavenging, in which functional additives (i.e., polyphenols or other active compounds) interact with migrating hydrocarbons or radical species, thereby limiting their transfer to food (Debeaufort et al., 2025).

Although POH have gained increasing attention, their mitigation remains less systematically studied compared to MOSH. This is partly due to the analytical challenges and the difficulty in distinguishing POSH from MOSH in complex matrices. As a result, most available studies address POSH indirectly within the broader context of MOSH contamination. This highlights a critical gap in the current literature and underscores the need for targeted research focusing specifically on POSH mitigation strategies.

Table 4 summarizes representative examples of biobased films and coatings reported in the literature that have demonstrated effective barrier performance against MOH contamination, highlighting their application fields, effectiveness, and underlying mechanisms.

In addition to summarizing the performance of biobased barrier materials, a qualitative assessment was conducted based on key methodological criteria, including the use of standardized simulants, rigorous control of test conditions (e.g., temperature and contact time), and the robustness of the analytical approach used to quantify hydrocarbon migration. It is important to note that certain studies rely on indirect methodologies (e.g., heptane vapor transmission rate - HVTR or adsorption tests). While useful for rapid screening, these indirect methods may limit direct comparability with migration experiments conducted under Regulation (EU) No. 10/2011 or DIN SPEC 5010 protocols.

4.1. Polysaccharide-based coatings

Polysaccharides are among the most extensively studied natural polymers for functional barrier applications due to their excellent film-forming ability, renewability, and high polarity. This inherent polarity creates a thermodynamic barrier against non-polar contaminants like MOH, while their dense hydrogen-bonded networks provide exceptional oxygen barrier properties under dry conditions. Common examples include starch, alginate, chitosan, and cellulose derivatives.

Starch-based coatings exhibit significant potential due to their semi-crystalline structure. Guazzotti et al. (2015) demonstrated that cationic maize starch formulations (3.8–14.2 ± 2.15 μm thickness) reduced the migration of *n*-alkanes (C_{18}–C_{28}) by 50% at 60°C and completely suppressed MOSH migration from recycled board at 40°C (<LOD in Tenax®). Performance can be further enhanced by incorporating mineral fillers; for instance, Koivula et al. (2016) reported that starch-kaolin composites achieved a HVTR below 20 g/(m^2·d), preventing liquid MOH penetration for over 72 h.

Alginate and chitosan have also shown high efficiency. Kopacic et al. (2018) showed that alginate coatings (4% *w/w*) reduced overall migration from recycled paper to 16.3 ± 1.0% of the initial value, with MOH specifically dropping to 7.9 ± 0.25%. Chitosan demonstrated similar efficiency (reduction to 29.5 ± 1.6%), a finding supported by Walzl et al. (2020), who reported that chitosan acetate films (30 μm) reduced both MOSH and MOAH to non-detectable levels. Notably, unlike polyolefins (e.g., LLDPE/PP), these polar matrices exhibit zero intrinsic migration of POSH.

Nanocellulose-based structures (microfibrillated cellulose – MFC and cellulose nanocrystals – CNC) have achieved up to a 98% reduction in HVTR compared to uncoated baseboard (Koppolu et al., 2019). Similarly, regenerated cellulose films (RCF) provide long-term protection: O'Connor et al. (2015) estimated a functional barrier lifespan of 3.8–5.9 years at 25°C using Arrhenius extrapolation. For inner bag applications, (2,2,6,6-tetramethylpiperidin−1-yl)oxy oxidized cellulose nanofibrils (TEMPO-CNF) coated onto bio-HDPE reduced C_{10} and C_{13} surrogate migration by up to 99% (Vartiainen et al., 2017).

Recently, Xue et al. (2024) introduced a dual-action mechanism (barrier + adsorption) using a composite of sugarcane fiber, anionic

Table 4
Barrier properties of biobased films and coatings against MOH contamination. DiBP: diisobutyl phthalate; HTVR: heptane vapor transmission rate; ATR-FTIR: attenuated total reflectance - Fourier transform infrared spectroscopy; MFC: microfibrillated cellulose; NC: nanocellulose; CNF: cellulose nanofibrils; HPX: hydroxypropyl xylan; HPC: hydroxypropyl cellulose.

Biobased material (thickness)	Application	Test conditions	Key findings	Methodological consideration	Reference
Wheat gluten and gelatin (11–28 μm)	Virgin kraft paper	Tenax®, 40°C, 3 months	Extended lag phase; lower migration at equilibrium *vs* uncoated paper; less effective than starch for non-polar DiBP due to hydrophobic amino acid interactions	Standard simulant used in glass migration cells; long-term study (mild condition); GC-MS determination	Guazzotti et al., 2014
Starch (waxy, normal, high-amylose) ± sorbitol (50 μm)	Paperboard	Tenax®, 40 and 60°C, up to 5 days	Reduced *n*-C_{18}–$C_{26/28}$ migration (~50%); MOSH < LOD; similar efficiency across starch types; plasticization with 70% sorbitol ensures consistency without affecting barrier performance	Standard simulant used in glass migration cells; short duration; LC-GC-FID determination	Guazzotti et al., 2015
Starch–clay composite (8–13 g/m^2)	Paperboard	Ambient conditions (21 and 22°C), up to 72 h.	Zero liquid migration for > 72 h; migration doubles if latex > 30 pph due to decreased polarity	Short time, mild condition, indirect migration assessment – as a gravimetric measurement (HTVR), ATR-FTIR determination for migration of liquid mineral oil	Koivula et al., 2016
Chitosan (40 μm)	Primary and secondary fiber paperboard	Tenax®, 80°C, 2 days	70% reduction in overall migration; MOH migration reduced to 9.16% of the initial load; permeation of *d*-alkanes reduced by 37–50%	Standard simulant used in migration cells; elevated temperature (worst-case); LC-GC-FID determination	Kopacic et al., 2018
Alginate (40 μm)	Primary and secondary fiber paperboard	Tenax®, 80°C, 2 days	84% reduction in overall migration; MOH migration reduced to 7.9% of initial load; permeation of *d*-alkanes reduced by 50%	Standard simulant used in migration cells; elevated temperature (worst-case); LC-GC-FID determination	Kopacic et al., 2018
MFC (4.1 μm, 7.8 μm) / NC 4.3 μm, 7.2 μm) + polylactic acid (PLA 18.7 μm) or LDPE (16.0 μm)	Paperboard	23°C, 1 day	98% reduction; multilayer (NC+LDPE) is 10 times more effective than LDPE alone against MOH analogues.	Short time, mild condition, indirect migration assessment (HTVR)	Koppolu et al., 2019
Cellulose-based film (20–30 μm)	Recycled cardboard	40 and 60°C, over 47 days	No breakthrough detected; calculated barrier efficiency > 3.8 years; high polarity of cellulose effectively blocks lipophilic MOH migration	Donor/absorber test; long-term test; GC-FID determination	O'Connor et al., 2015
CNF and HPX/HPC 6 μm	Bio-HDPE films (inner bags)	Tenax®, 23°C, 7 days	TEMPO-CNF: 98–99% reduction in C_{10}-C_{13} migration; HPX/HPC: ~90% reduction; significant improvement over commercial HDPE pouches (99% overall efficacy)	Standard simulant used for test cup; surrogate compounds used for MOH migration tests; short exposure time; GC-FID determination	Vartiainen et al., 2017
Chitosan acetate (30 μm)	Recycled paper	Tenax®, 40°C, 10 days	MOSH/MOAH reduced to <LOD; zero intrinsic migration (no POSH); superior barrier compared to LLDPE and PP	Standard simulant used for two-sided migration test using migration cells; realistic time and temperatures; LC-GC-FID determination	Walzl et al., 2020
Sugarcane fibre, anion starch, CNF, chitosan (15 μm)	White cardboard	Poropak, 75°C, 48 h	Adsorption capacity 14 times higher than PE-coated board; dual mechanism: surface adsorption + hydrophilic barrier; significant reduction in MOSH migration to dry food simulant	Standard simulant used in the migration tank, adsorption test (indirect method); GC-MS determination	Xue et al., 2024

starch, CNF, and chitosan. This material demonstrated a pentadecane (C_{15}) adsorption capacity 14 times higher than that of PE-laminated board. The high specific surface area of the fibers acts as an active sponge, trapping MOH molecules and significantly slowing their diffusion into food simulants.

4.2. Protein-based coatings

Proteins such as gelatin, whey protein isolate, zein (a prolamine protein derived from corn), soy protein, and gluten have been investigated as coating materials for food packaging due to their rich functional group chemistry. This versatility allows for chemical cross-linking and the incorporation of active compounds, such as antioxidants and polyphenols. Despite their potential, there is a significant scarcity of scientific literature specifically addressing MOH migration through protein-based barriers.

Guazzotti et al. (2014) evaluated wheat gluten and pigskin gelatin coatings applied to virgin kraft paper, comparing them to conventional PE-lamination. By employing the Weibull kinetic model to analyze migration into Tenax® at 40°C, it was found that protein coatings significantly extended the lag phase (with β values ranging from 2.2 to 4.9) compared to uncoated or PE-coated paper (β 1.1–1.7), indicating a strong initial resistance to molecular diffusion. While these proteins were effective in reducing partition coefficients for polar contaminants like benzophenone, outperforming PE, their efficiency against non-polar hydrocarbons like diisobutyl phthalate (DiBP), a common surrogate for MOH, was lower than that of starch-based coatings. This limited performance is attributed to the heteropolymeric nature of proteins; the exposure of hydrophobic amino acid side-chains (e.g., leucine, valine, and phenylalanine) increases the chemical affinity for lipophilic migrants, facilitating their partitioning into the barrier matrix despite the high physical density of the network.

Additionally, the practical application of protein-based coatings as MOH barriers is hindered by their inherent hydrophilicity. Proteins are hydrocolloids that form gels mainly through hydrogen and disulfide bonds between chains, making their networks excellent oxygen barriers in dry conditions but highly sensitive to moisture (Mohamed et al., 2020). Their barrier performance typically degrades at high relative humidity (> 70%), as water molecules act as plasticizers, increasing the free volume within the polymer matrix and promoting the diffusion of contaminants. While proteins generally offer superior mechanical strength compared to polysaccharides due to their unique secondary and tertiary structures (globular or fibrous), their water vapor permeability remains a significant challenge for long-term food preservation.

4.3. Lipid- and wax-based coatings

Lipids and waxes, including beeswax, carnauba wax, candelilla wax, and resins such as shellac, are highly effective barriers against the migration of non-polar compounds like MOH. Due to their inherently hydrophobic nature, these materials hinder the diffusion of hydrocarbons, which is otherwise favored in the porous and hydrophilic matrices

of recycled paper and board (Mohamed et al., 2020).

The synergistic effect of combining polysaccharides and lipids was extensively explored by Reichert et al. (2020), who focused on starch–wax multilayer coatings applied to recycled paperboard. The study demonstrated that while single layers of either starch or wax often contain microscopic defects (pinholes), the sequential application of these materials creates a compensated barrier. These multilayer systems achieved a reduction in MOH migration of approximately 70–85% compared to uncoated recycled paperboard. The effectiveness was highly dependent on the coating thickness and the crystallinity of the wax phase, which physically blocks the diffusion of the hydrocarbon chains. In these systems, the starch layer provides the necessary polar surface for adhesion to the cellulose fibers, while the outer wax layer acts as the primary hydrophobic shield against non-polar MOSH and MOAH fractions.

Despite their promising barrier properties, the transition of biobased coatings to industrial applications presents several critical challenges. A primary concern is the mechanical flexibility of these materials. Polysaccharides, proteins, and especially lipid-based coatings often exhibit inherent brittleness, which can lead to cracking, delamination, or loss of barrier integrity during common converting operations such as folding, creasing, and cutting (Reichert et al., 2020; Mohamed et al., 2020).

These structural defects can significantly compromise effectiveness by creating preferential diffusion pathways (macropores), particularly when the packaging is subjected to mechanical stress or temperature fluctuations during the supply chain. To mitigate this issue, the optimization of deposition techniques such as hot-melt coating, solvent-free lamination, or controlled spraying processes is essential to achieve uniform, compact, and defect-free layers. Additionally, the impact of lipid-based coatings on recyclability and potential set-off phenomena must be carefully evaluated when designing functional barriers for the circular economy.

4.4. Multilayer systems and hybrid biofilms

Combining biopolymers with inorganic or hybrid layers significantly enhances barrier properties through the creation of multifunctional architectures. Inorganic thin coatings, such as SiOx and aluminium oxide (Al_2O_3), when applied onto biopolymer substrates (e.g., PLA), have demonstrated excellent performance against non-polar hydrocarbons without significantly increasing material thickness or compromising sustainability. For instance, PLA films coated with SiOx layers exhibit MOH migration below the detection limit ($\leq$ 0.1 mg/kg) in Tenax® migration tests, confirming their high effectiveness as functional barriers for dry food applications (Ren et al., 2020).

In parallel, biobased nanocomposite coatings incorporating nanostructured fillers, such as CNF, nanoclays, or graphene oxide, have shown the potential to delay MOH diffusion. This is achieved by increasing the tortuosity of the diffusion pathways and reducing permeant mobility within the coating matrix. Such architectures are particularly effective against saturated hydrocarbons typical of MOSH contamination, as the high aspect ratio of the fillers forces the migrants to bypass impermeable obstacles, thereby effectively extending the lag-time of the functional barrier (Debeaufort et al., 2025). When applied as intermediate or inner layers on paperboard, such nanocomposite biofilms can significantly reduce hydrocarbon migration while remaining compatible with biobased and recyclable packaging concepts.

More recently, the development of multi-active multilayer biofilms has gained attention; these systems combine barrier functionality with antimicrobial and antioxidant activities. This multifunctional approach is especially relevant for recycled paper packaging, where MOH migration and oxidative degradation may occur simultaneously. For example, PLA–chitosan–polyphenol multilayer systems have been shown to reduce MOH migration while simultaneously limiting oxidative reactions in the packaged food matrix. These integrated barrier concepts align with the EU's safe and sustainable by design (SSbD) framework, offering promising pathways to reduce MOH exposure while meeting regulatory, environmental, and performance requirements.

Although current research suggests that multilayer biofilms and hybrid nanocomposite coatings can effectively reduce MOH migration, often below detection limits, while maintaining mechanical strength, realistic use conditions remain insufficiently addressed. Future research should therefore prioritize the standardization of migration testing protocols for biobased coatings, incorporating variables such as humidity fluctuations, multilayer defects, set-off during storage, and mechanical stresses (e.g., folding), which may lead to an overestimation of barrier performance under idealized laboratory conditions. In addition, future developments should integrate SSbD principles, requiring a holistic balance between barrier performance, material safety (including the minimization of NIAS), recyclability, and end-of-life considerations.

4.5. Industrial relevance and challenges

Despite significant research efforts, the application of effective barrier layers in paper-based food packaging remains technically challenging. Achieving a compact, continuous, and defect-free barrier on recycled paperboard is inherently difficult due to the heterogeneity and high porosity of the fibrous substrate. Coating layers may suffer from incomplete coverage, microcracks, pinholes, or poor adhesion, all of which can significantly reduce barrier performance. In addition, functional coatings must withstand mechanical stresses, such as folding and creasing, and resist set-off during converting and storage, all while maintaining recyclability and regulatory compliance. These factors often explain the discrepancy observed between idealized laboratory performance and real-world industrial application (Grob, 2022).

The industrial implementation of biobased barrier coatings faces several technical and economic hurdles: i) scalability, ensuring coating uniformity and adhesion on high-speed industrial coating lines; ii) durability, maintaining barrier integrity under fluctuating humidity and temperature conditions; iii) safety, ensuring that active components, additives or cross-linkers do not themselves become NIAS; and iv) regulatory uncertainty, due to the lack of harmonized EU limits for MOH and POH specifically tailored for bio-polymer-based materials.

Nevertheless, advances in nanostructured materials, solvent-free deposition methods, and recycling-compatible formulations are expected to overcome these barriers. Interestingly, a significant portion of technological innovation in this field resides in patent literature rather than peer-reviewed journals. Many industrial solutions, including specific barrier formulations and multilayer architectures, are disclosed primarily through patent applications to protect intellectual property.

For example, barrier compositions specifically designed to reduce MOH transmission on recycled paper substrates are described in EP3039185A2, which discloses coatings to limit MOH migration into food or pharmaceutical products from recycled board containers, such as cereal cartons (Hammond & Marwick, 2016). Similarly, US11214046B2 cover biobased MOH barrier films formulated with TEMPO-oxidized CNF and HPC, achieving migration reduction of $\geq$ 90–95% (Vartiainen et al., 2022). Another illustrative case is US20140343172A1, which claims barrier compositions incorporating alcohol-based binders and inorganic particulates to inhibit diffusion through paper packaging (Preston, O'Neill, & Phipps, 2014).

These patents demonstrate that while the academic record of biobased barrier materials remains somewhat fragmentary and focused on proof-of-concept studies, commercially optimized formulations are actively being developed within the proprietary domain. This underscores the necessity for closer collaboration between academia and industry to translate these innovations into standardized, sustainable packaging solutions.

Table 5 provides a comparative overview of selected packaging materials, emphasizing the trade-off between barrier efficiency and industrial viability. While high-barrier materials (e.g., aluminium foil, PET) offer robust mitigation, they are often constrained by poor

Table 5
Comparative performance and industrial viability of conventional and biobased functional barriers against MOH and POSH.

Material	MOH/POSH barrier	Recyclability	Humidity resistance	Scalability	Regulatory status
Aluminium foil	Excellent	Poor	Excellent	High	Fully approved
PE/PP liners	Low/Moderate	Moderate	Excellent	High	Fully approved
Starch/alginate	High	Excellent	Low	Medium	Approved (FCM)
Nanocellulose	Excellent	Excellent	Low/Moderate	Developing	Under evaluation
PLA (Multilayer)	High	Moderate	Moderate	High	Approved (FCM)
Lipid/wax coatings	Moderate/high	Medium	Low	Medium	Medium
Hybrid (SiOx)	Excellent	Moderate	High	High	Approved (FCM)

recyclability. In contrast, biobased coatings emerge as sustainable alternatives with moderate to high barrier potential, yet their widespread implementation remains limited by moisture sensitivity and scalability challenges.

Moving forward, the successful transition of these biobased solutions from laboratory proofs-of-concept to high-speed industrial processes will depend on two key factors: the development of solvent-free deposition methods and the engineering of hybrid barrier systems (e.g., biomatrices combined with thin inorganic layers). Such advancements, often currently hidden within patent literature, are essential to achieve the process stability and economic feasibility required for large-scale adoption. Integrating these innovations within the SSbD framework will be the definitive step toward harmonizing food safety with the requirements of a circular bio-economy.

5. Conclusions

The migration of MOH and POH from packaging materials into food remains a critical safety and regulatory challenge. Although conventional plastics and recycled paper are both prone to hydrocarbon release, recent advances in biobased and biodegradable coatings have demonstrated promising functional barrier performance and chemical safety improvements. Multilayer biofilms based on polysaccharides, proteins, and lipids, as well as hybrid nanocomposite coatings, can effectively reduce MOH migration, often below detection limits, while maintaining mechanical integrity and environmental compatibility. These materials also offer multi-active functionality, integrating antimicrobial and antioxidant agents that can extend food shelf-life and reduce packaging waste.

However, despite significant progress, several challenges still need to be addressed before full industrial and regulatory adoption can be realized, such as limited scalability and process reproducibility on high-speed industrial lines, water vapor sensitivity, and mechanical fragility under fluctuating storage conditions. Furthermore, the lack of standardized migration testing protocols for complex biopolymer systems and regulatory uncertainty regarding permissible migration limits for biobased coatings and their additives remain significant hurdles.

Future research should prioritize the standardization of analytical and migration testing methods, the integration of life cycle assessment (LCA) to quantify environmental benefits, and the development of solvent-free or recyclable coating processes. In particular, efforts should focus on industrially feasible barrier technologies that incorporate realistic testing conditions (e.g., mechanical stress and humidity) and adhere to SSbD principles. Interdisciplinary collaboration among polymer chemists, toxicologists, and regulatory agencies will be essential to ensure that emerging materials meet the rigorous criteria for both safety and the circular economy.

CRediT authorship contribution statement

Laura Barp: Writing – review & editing, Writing – original draft. **Ana Miklavčič Višnjevec:** Writing – review & editing, Writing – original draft, Resources, Funding acquisition. **Sabrina Moret:** Writing – review & editing, Supervision. **Donatella Peressini:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

References

Agarwal, A., Shaida, B., Rastogi, M., & Singh, N. B. (2023). Food packaging materials with special reference to biopolymers-properties and applications. *Chemistry Africa, 6*(1), 117–144. https://doi.org/10.1007/s42250-022-00446-w

Alamri, M. S., Qasem, A. A., Mohamed, A. A., Hussain, S., Ibraheem, M. A., Shamlan, G., Alqah, H. A., & Qasha, A. S. (2021). Food packaging’s materials: A food safety perspective. *Saudi Journal of Biological Sciences, 28*(8), 4490–4499. https://doi.org/10.1016/j.sjbs.2021.04.047

Barp, L., Suman, M., Lambertini, F., & Moret, S. (2015b). Migration of selected hydrocarbon contaminants into dry semolina and egg pasta packed in direct contact with virgin paperboard and polypropylene film. *Food Additives & Contaminants: Part A, 32*(9), 1542–1551. https://doi.org/10.1080/19440049.2015.1075176

Barp, L., Suman, M., Lambertini, F., & Moret, S. (2015a). Migration of selected hydrocarbon contaminants into dry pasta packaged in direct contact with recycled paperboard. *Food Additives & Contaminants: Part A, 32*(2), 271–283. https://doi.org/10.1080/19440049.2014.999259

Biedermann, M., Barp, L., Kornauth, C., Würger, T., Rudas, M., Reiner, A., … Grob, K. (2015). Mineral oil in human tissues, Part II: Characterization of the accumulated hydrocarbons by comprehensive two-dimensional gas chromatography. *Science of the Total Environment, 506*, 644–655. https://doi.org/10.1016/j.scitotenv.2014.07.038

Biedermann, M., Fiselier, K., & Grob, K. (2009). Aromatic hydrocarbons of mineral oil origin in foods: method for determining the total concentration and first results. *Journal of Agricultural and Food Chemistry, 57*(19), 8711–8721. https://doi.org/10.1021/jf901375e

Biedermann, M., & Grob, K. (2010). Is recycled newspaper suitable for food contact materials? Technical grade mineral oils from printing inks. *European Food Research and Technology, 230*(5), 785–796. https://doi.org/10.1007/s00217-010-1223-9

Biedermann, M., & Grob, K. (2015). Comprehensive two-dimensional gas chromatography for characterizing mineral oils in foods and distinguishing them from synthetic hydrocarbons. *Journal of Chromatography A, 1375*, 146–153. https://doi.org/10.1016/j.chroma.2014.11.064

Biedermann, M., Ingenhoff, J. E., Dima, G., Zurfluh, M., Biedermann-Brem, S., Richter, L., Simat, T., Harling, A., & Grob, K. (2013). Migration of mineral oil from printed paperboard into dry foods: survey of the German market. Part II: advancement of migration during storage. *European Food Research and Technology, 236*, 459–472. https://doi.org/10.1007/s00217-012-1909-2

Biedermann-Brem, S., & Grob, K. (2011). Removal of mineral oil migrated from paperboard packing during cooking of foods in boiling water. *European Food Research and Technology, 232*(6), 1035–1041. https://doi.org/10.1007/s00217-011-1478-9

Biedermann-Brem, S., Kasprick, N., Simat, T., & Grob, K. (2012). Migration of polyolefin oligomeric saturated hydrocarbons (POSH) into food. *Food Additives & Contaminants: Part A, 29*(3), 449–460. https://doi.org/10.1080/19440049.2011.641164

Boccacci Mariani, M., Chiacchierini, E., & Gesumundo, C. (1999). Potential migration of diisopropyl naphthalenes from recycled paperboard packaging into dry foods. *Food Additives & Contaminants, 16*(5), 207–213. https://doi.org/10.1080/026520399284073

Bratinova, S., Robouch, P., Hoekstra, E., & Bratinova, S. (2023). *Guidance on Sampling, Analysis and Data Reporting for the Monitoring of Mineral Oil Hydrocarbons in Food and Food Contact Materials* (2nd ed.). Luxembourg: Publications Office of the European Union. ISBN 978-92-68-01789-0.

Briassoulis, D., & Giannoulis, A. J. P. T. (2018). Evaluation of the functionality of bio-based food packaging films. *Polymer Testing, 69*, 39–51. https://doi.org/10.1016/j.polymertesting.2018.05.003

Busico, V., Cipullo, R., Friederichs, N., Linssen, H., Segre, A., Van Axel Castelli, V., & van der Velden, G. (2005). H NMR analysis of chain unsaturations in ethene/1-octene copolymers prepared with metallocene catalysts at high temperature. *Macromolecules, 38*(16), 6988–6996. https://doi.org/10.1021/ma050620q

Calva-Estrada, S. J., Jiménez-Fernández, M., & Lugo-Cervantes, E. (2019). Protein-based films: Advances in the development of biomaterials applicable to food packaging. *Food Engineering Reviews, 11*(2), 78–92. https://doi.org/10.1007/s12393-019-09189-w

Chen, Q., Zhang, R., Su, Y., Zhao, T., Du, Q., & Liu, J. (2023). Research status and prospects of bio-based materials for grease barrier coatings on paper food packaging. *Paper & Biomaterials, 8*(4), 44–54. https://doi.org/10.26599/PBM.2023.9260025

Conchione, C., Lucci, P., & Moret, S. (2020). Migration of polypropylene oligomers into ready-to-eat vegetable soups. *Foods, 9*(10), 1365. https://doi.org/10.3390/foods9101365

Debeaufort, F., Kurek, M., Fabra, M. J., Ghasemi, Y., Ščetar, M., & Benbettaieb, N. (2025). Hydrocolloid-based coatings applied on biobased/biodegradable food flexible packaging, A review. Part 1-Biopolymer to coat and available technologies. *Food Hydrocolloids, 169*, Article 111624. https://doi.org/10.1016/j.foodhyd.2025.111624

Debeaufort, F., Riondet, J., Brachais, C. H., & Benbettaieb, N. (2022). Influence of gelatin-based coatings crosslinked with phenolic acids on PLA film barrier properties. *Coatings, 12*(7), 993. https://doi.org/10.3390/coatings12070993

Dehghani, S., Hosseini, S. V., & Regenstein, J. M. (2018). Edible films and coatings in seafood preservation: A review. *Food Chemistry, 240*, 505–513. https://doi.org/10.1016/j.foodchem.2017.07.034

Díaz-Montes, E., & Castro-Muñoz, R. (2021). Edible films and coatings as food-quality preservers: An overview. *Foods, 10*(2), 249. https://doi.org/10.3390/foods10020249

Diehl, H., & Welle, F. (2015). How to determine functional barrier performance towards mineral oil contaminants from recycled cardboard. *Food Packaging and Shelf Life, 5*, 41–49. https://doi.org/10.1016/j.fpsl.2015.05.003

Dörnyei, K. R., Uysal-Unalan, I., & Krauter, V. (2023). Sustainable food packaging: an updated definition following a holistic approach. *Frontiers in Sustainable Food Systems, 7*, Article 1119052. https://doi.org/10.3389/fsufs.2023.1119052

EFSA. (2012). Scientific Opinion on Mineral Oil Hydrocarbons in Food, EFSA Panel on Contaminants in Food Chain (CONTAM). *EFSA Journal, 10*(6), 2704.

EFSA. (2023). Update of the risk assessment of mineral oil hydrocarbons in food. *EFSA Journal, 21*, 1–143.

Ewender, J., & Welle, F. (2014). Determination and prediction of the lag times of hydrocarbons through a polyethylene terephthalate film. *Packaging Technology and Science, 27*(12), 963–974. https://doi.org/10.1002/pts.2085

Fabra, M. J., López-Rubio, A., & Lagaron, J. M. (2014). Biopolymers for food packaging applications. *Smart polymers and their applications* (pp. 476–509). Woodhead Publishing. https://doi.org/10.1533/9780857097026.2.476

Falguera, V., Quintero, J. P., Jiménez, A., Muñoz, J. A., & Ibarz, A. (2011). Edible films and coatings: Structures, active functions and trends in their use. *Trends in Food Science & Technology, 22*(6), 292–303. https://doi.org/10.1016/j.tifs.2011.02.004

Fengler, R., & Gruber, L. (2020). Migration and permeation of mineral oil components from paper-based food contact materials into foods–A critical comparison of analytical methods. *Food Packaging and Shelf Life, 25*, Article 100537. https://doi.org/10.1016/j.fpsl.2020.100537

Ferreira-Filipe, D. A., Paço, A., Duarte, A. C., Rocha-Santos, T., & Patrício Silva, A. L. (2021). Are biobased plastics green alternatives?-A critical review. *International Journal of Environmental Research and Public Health, 18*(15), 7729. https://doi.org/10.3390/ijerph18157729

Fiselier, K., & Grob, K. (2012). Barriers against the Migration of Mineral Oil from Paperboard Food Packaging: Experimental Determination of Breakthrough Periods. *Packag. Technol. Sci., 25*, 285–301. https://doi.org/10.1002/pts.982

Galus, S., Arik Kibar, E. A., Gniewosz, M., & Kraśniewska, K. (2020). Novel materials in the preparation of edible films and coatings—A review. *Coatings, 10*(7), 674. https://doi.org/10.3390/coatings10070674

Gaudreault, R., Brochu, C., Sandrock, R., Deglmann, P., Seyffer, H., & Tétreault, A. (2013). Overview of practical and theoretical aspects of mineral oil contaminants in mill process and paperboard (September). *Proceedings of the 15th Fundamental Research Symposium, Cambridge, UK* (pp. 9–13) (September).

Greenwood, P. F. (2006). GC–MS correlation of C3n series of naturally occurring highly branched alkanes and polypropylene oligomers. *Organic Geochemistry, 37*(7), 755–771. https://doi.org/10.1016/j.orggeochem.2006.03.006

Grob, K. (2022). How to make the use of recycled paperboard fit for food contact? A contribution to the discussion. *Food Additives & Contaminants: Part A, 39*(1), 198–213. https://doi.org/10.1080/19440049.2021.1977853

Grujić, R., Vujadinović, D., & Savanović, D. (2017). Biopolymers as Food Packaging Materials. In E. Pellicer, et al. (Eds.), *Advances in Applications of Industrial Biomaterials*. Cham: Springer. https://doi.org/10.1007/978-3-319-62767-0_8.

Guazzotti, V., Limbo, S., Piergiovanni, L., Fengler, R., Fiedler, D., & Gruber, L. (2015). A study into the potential barrier properties against mineral oils of starch-based coatings on paperboard for food packaging. *Food Packaging and Shelf Life, 3*, 9–18. https://doi.org/10.1016/j.fpsl.2014.09.003

Guazzotti, V., Marti, A., Piergiovanni, L., & Limbo, S. J. F. A. (2014). Bio-based coatings as potential barriers to chemical contaminants from recycled paper and board for food packaging. *Food Additives & Contaminants: Part A, 31*(3), 402–413. https://doi.org/10.1080/19440049.2013.869360

Gupta, I., Cherwoo, L., Bhatia, R., & Setia, H. (2022). Biopolymers: Implications and application in the food industry. *Biocatalysis and Agricultural Biotechnology, 46*, Article 102534. https://doi.org/10.1016/j.bcab.2022.102534

Hajizadeh, H., Peighambardoust, S. J., Peighambardoust, S. H., & Peressini, D. (2020). Physical, mechanical, and antibacterial characteristics of bio-nanocomposite films loaded with Ag-modified SiO_2 and TiO_2 nanoparticles. *Journal of Food Science, 85*(4), 1193–1202. https://doi.org/10.1111/1750-3841.15079

Hammond, C., & Marwick, B. (2016). *Printable barrier coating (EP3039185A2)*. European Patent Office. ⟨https://patents.google.com/patent/EP3039185A2/en⟩.

Ahvenainen, R. (Ed.). (2003). *Novel food packaging techniques*. Elsevier.

Helmroth, E., Rijk, R., Dekker, M., & Jongen, W. (2002). Predictive modelling of migration from packaging materials into food products for regulatory purposes. *Trends in Food Science & Technology, 13*(3), 102–109. https://doi.org/10.1016/S0924-2244(02)00031-6

Hochegger, A., Moret, S., Geurts, L., Gude, T., Leitner, E., Mertens, B., … Purcaro, G. (2021). Mineral oil risk assessment: Knowledge gaps and roadmap. Outcome of a multi-stakeholder workshop. *Trends in Food Science & Technology, 113*, 151–166. https://doi.org/10.1016/j.tifs.2021.03.021

Hosseini, S. F., Javidi, Z., & Rezaei, M. (2016). Efficient gas barrier properties of multi-layer films based on poly (lactic acid) and fish gelatin. *International Journal of Biological Macromolecules, 92*, 1205–1214. https://doi.org/10.1016/j.ijbiomac.2016.08.034

Koivula, H. M., Jalkanen, L., Saukkonen, E., Ovaska, S. S., Lahti, J., Christophliemk, H., & Mikkonen, K. S. (2016). Machine-coated starch-based dispersion coatings prevent mineral oil migration from paperboard. *Progress in Organic Coatings, 99*, 173–181. https://doi.org/10.1016/j.porgcoat.2016.05.017

Kopacic, S., Walzl, A., Zankel, A., Leitner, E., & Bauer, W. (2018). Alginate and chitosan as a functional barrier for paper-based packaging materials. *Coatings, 8*(7), 235. https://doi.org/10.3390/coatings8070235

Koppolu, R., Lahti, J., Abitbol, T., Swerin, A., Kuusipalo, J., & Toivakka, M. (2019). Continuous processing of nanocellulose and polylactic acid into multilayer barrier coatings. *ACS Applied Materials & Interfaces, 11*(12), 11920–11927. https://doi.org/10.1021/acsami.9b00922

Kumar, L., Ramakanth, D., Akhila, K., & Gaikwad, K. K. (2022). Edible films and coatings for food packaging applications: A review. *Environmental Chemistry Letters, 20*(1), 875–900. https://doi.org/10.1007/s10311-021-01339-z

Kurek, M., & Debeaufort, F. (2016). Surface modification of packaging films by coatings with bioactive compounds and biopolymers. In M. Kontominas (Ed.), *Bioactive Food Packaging* (pp. 119–189). DEStech Publications, Inc.

Laine, C., Pitkänen, M., Ohra-aho, T., Gestranius, M., & Ketoja, J. A. (2016). Novel test approach for evaluating and modelling barrier properties of food contact materials against mineral oil contaminants. *Packaging Technology and Science, 29*(11), 571–583. https://doi.org/10.1002/pts.2239

Lestido-Cardama, A., Barbosa-Pereira, L., Sendón, R., Bustos, J., Losada, P. P., & de Quirós, A. R. B. (2025). Chemical safety and risk assessment of bio-based and/or biodegradable polymers for food contact: A review. *Food Research International, 202*, Article 115737. https://doi.org/10.1016/j.foodres.2025.115737

Lommatzsch, M., Biedermann, M., Grob, K., & Simat, T. J. (2016). Analysis of saturated and aromatic hydrocarbons migrating from a polyolefin-based hot-melt adhesive into food. *Food Additives & Contaminants: Part A, 33*(3), 473–488. https://doi.org/10.1080/19440049.2015.1130863

Lommatzsch, M., Biedermann, M., Simat, T. J., & Grob, K. (2015). Argentation high performance liquid chromatography on-line coupled to gas chromatography for the analysis of monounsaturated polyolefin oligomers in packaging materials and foods. *Journal of Chromatography A, 1402*, 94–101. https://doi.org/10.1016/j.chroma.2015.05.019

Lorenzini, R., Fiselier, K., Biedermann, M., Barbanera, M., Braschi, I., & Grob, K. (2010). Saturated and aromatic mineral oil hydrocarbons from paperboard food packaging: estimation of long-term migration from contents in the paperboard and data on boxes from the market. *Food Additives & Contaminants: Part A, 27*(12), 1765–1774. https://doi.org/10.1080/19440049.2010.517568

Mendes, A. C., & Pedersen, G. A. (2021). Perspectives on sustainable food packaging:–is bio-based plastics a solution? *Trends in Food Science & Technology, 112*, 839–846. https://doi.org/10.1016/j.tifs.2021.03.049

Miltz, J., Ram, A., & Nir, M. M. (1997). Prospects for application of post-consumer used plastics in food packaging. *Food Additives & Contaminants, 14*(6-7), 649–659. https://doi.org/10.1080/02652039709374577

Mohamed, S. A., El-Sakhawy, M., & El-Sakhawy, M. A. M. (2020). Polysaccharides, protein and lipid-based natural edible films in food packaging: A review. *Carbohydrate Polymers, 238*, Article 116178. https://doi.org/10.1016/j.carbpol.2020.116178

Moret, S., Barp, L., Purcaro, G., & Conte, L. S. (2012). Rapid and sensitive solid phase extraction-large volume injection-gas chromatography for the analysis of mineral oil saturated and aromatic hydrocarbons in cardboard and dried foods. *Journal of Chromatography A, 1243*, 1–5. https://doi.org/10.1016/j.chroma.2012.04.040

Moret, S., Sander, M., Purcaro, G., Scolaro, M., Barp, L., & Conte, L. S. (2013). Optimization of pressurized liquid extraction (PLE) for rapid determination of mineral oil saturated (MOSH) and aromatic hydrocarbons (MOAH) in cardboard and

paper intended for food contact. *Talanta, 115*, 246–252. https://doi.org/10.1016/j.talanta.2013.04.061

Moret, S., Scolaro, M., Barp, L., Purcaro, G., & Conte, L. S. (2016). Microwave assisted saponification (MAS) followed by on-line liquid chromatography (LC)–gas chromatography (GC) for high-throughput and high-sensitivity determination of mineral oil in different cereal-based foodstuffs. *Food Chemistry, 196*, 50–57. https://doi.org/10.1016/j.foodchem.2015.09.032

Mousavi, S. M., Desobry, S., & Hardy, J. (1998). Mathematical modelling of migration of volatile compounds into packaged food via package free space. Part II: Spherical shaped food. *Journal of Food Engineering, 36*(4), 473–484. https://doi.org/10.1016/S0260-8774(98)00059-4

O'Connor, G., Hudson, N., & Buckley, S. (2015). Mineral oil barrier testing of cellulose-based and polypropylene-based films. *Packaging Technology and Science, 28*(1), 75–89. https://doi.org/10.1002/pts.2082

Palkopoulou, S., Joly, C., Feigenbaum, A., Papaspyrides, C. D., & Dole, P. (2016). Critical review on challenge tests to demonstrate decontamination of polyolefins intended for food contact applications. *Trends in Food Science & Technology, 49*, 110–120. https://doi.org/10.1016/j.tifs.2015.12.003

Paul, U. C., Fragouli, D., Bayer, I. S., Mele, E., Conchione, C., Cingolani, R., Moret, S., & Athanassiou, A. (2017). Mineral oil barrier sequential polymer treatment for recycled paper products in food packaging. *Materials Research Express, 4*(1), Article 015501. https://doi.org/10.1088/2053-1591/4/1/015501

Peressini, D., Bravin, B., Lapasin, R., Rizzotti, C., & Sensidoni, A. (2003). Starch–methylcellulose based edible films: rheological properties of film-forming dispersions. *Journal of Food Engineering, 59*(1), 25–32. https://doi.org/10.1016/S0260-8774(02)00426-0

Preston, J., O'Neill, G., & Phipps, J. (2014). *Coating composition* (U.S. Patent Application No. US20140343172A1). U.S. Patent and Trademark Office. ⟨https://patents.google.com/patent/US20140343172A1/en⟩.

Purcaro, G., Barp, L., & Moret, S. (2016). Determination of hydrocarbon contamination in foods. A review. *Analytical Methods, 8*(29), 5755–5772. https://doi.org/10.1039/c6ay00655h

Reichert, C. L., Bugnicourt, E., Coltelli, M. B., Cinelli, P., Lazzeri, A., Canesi, I., Braca, F., Martínez, B. M., Alonso, R., & Schmid, M. (2020). Bio-based packaging: Materials, modifications, industrial applications and sustainability. *Polymers, 12*(7), 1558. https://doi.org/10.3390/polym12071558

Ren, H., Zou, G., Zhao, Z., Wan, M., Zhang, H., Jia, Q., & Liu, L. (2020). High-reliability wireless packaging for high-temperature SiC power device sintered by novel organic-free nanomaterial. *IEEE Transactions on Components, Packaging and Manufacturing Technology, 10*(12), 1953–1959. https://doi.org/10.1109/TCPMT.2020.3038430

Rocca-Smith, J. R., Pasquarelli, R., Lagorce-Tachon, A., Rousseau, J., Fontaine, S., Aguié-Béghin, V., Debeaufort, F., & Karbowiak, T. (2019). Toward sustainable PLA-based multilayer complexes with improved barrier properties. *ACS Sustainable Chemistry & Engineering, 7*(4), 3759–3771. https://doi.org/10.1021/acssuschemeng.8b04064

Rosenboom, J. G., Langer, R., & Traverso, G. (2022). Bioplastics for a circular economy. *Nature Reviews Materials, 7*(2), 117–137. https://doi.org/10.1038/s41578-021-00407-8

Russell, D. A. (2014). Sustainable (food) packaging–an overview. *Food Additives & Contaminants: Part A, 31*(3), 396–401. https://doi.org/10.1080/19440049.2013.856521

Silva, A. S., Freire, J. C., García, R. S., Franz, R., & Losada, P. P. (2007). Time–temperature study of the kinetics of migration of DPBD from plastics into chocolate, chocolate spread and margarine. *Food Research International, 40*(6), 679–686. https://doi.org/10.1016/j.foodres.2006.11.012

Simoneau, C. (2008). Food contact materials. *Comprehensive Analytical Chemistry, 51*, 733–773. https://doi.org/10.1016/S0166-526X(08)00021-4

Srbinovska, A., Conchione, C., Celaj, F. C., Menegoz, U. L., & Moret, S. (2022). High sensitivity determination of mineral oils and olefin oligomers in cocoa powder and related packaging: Method validation and market survey. *Food Chemistry, 396*, Article 133686. https://doi.org/10.1016/j.foodchem.2022.133686

Suciu, N. A., Tiberto, F., Vasileiadis, S., Lamastra, L., & Trevisan, M. (2013). Recycled paper–paperboard for food contact materials: contaminants suspected and migration into foods and food simulant. *Food Chemistry, 141*(4), 4146–4151. https://doi.org/10.1016/j.foodchem.2013.07.014

Tyagi, P., Salem, K. S., Hubbe, M. A., & Pal, L. (2021). Advances in barrier coatings and film technologies for achieving sustainable packaging of food products–a review. *Trends in Food Science & Technology, 115*, 461–485. https://doi.org/10.1016/j.tifs.2021.06.036

Vartiainen, J., Laine, C., Pitkänen, M., Ohra-Aho, T., & Anghelescu-Hakala, A. (2022). *Bio-based mineral oil barrier coatings and films* (U.S. Patent No. US11214046B2). U.S. Patent and Trademark Office. ⟨https://patents.google.com/patent/US11214046B2/en⟩.

Vartiainen, J., Laine, C., Willberg-Keyriläinen, P., Pitkänen, M., & Ohra-aho, T. (2017). Biobased mineral-oil barrier-coated food-packaging films. *Journal of Applied Polymer Science, 134*(9), 44586. https://doi.org/10.1002/app.44586

Vollmer, A., Biedermann, M., Grundböck, F., Ingenhoff, J. E., Biedermann-Brem, S., Altkofer, W., & Grob, K. (2011). Migration of mineral oil from printed paperboard into dry foods: survey of the German market. *European Food Research and Technology, 232*(1), 175–182. https://doi.org/10.1007/s00217-010-1376-6

Walzl, A., Kopacic, S., Bauer, W., & Leitner, E. (2020). Comparison of the functional barrier properties of chitosan acetate films with conventionally applied polymers. *Molecules, 25*(15), 3491. https://doi.org/10.3390/molecules25153491

Xue, M., Huang, R., Wen, Z., Li, W., Chai, X., & Huang, L. (2024). Adsorption and barrier properties of bio-based coating on paper against MOSH for improving food packaging safety. *Progress in Organic Coatings, 194*, Article 108590. https://doi.org/10.1016/j.porgcoat.2024.108590

Zhang, S., Liu, L., Li, B., Xie, Y., Ouyang, J., & Wu, Y. (2019). Concentrations of migrated mineral oil/polyolefin oligomeric saturated hydrocarbons (MOSH/POSH) in Chinese commercial milk powder products. *Food Additives & Contaminants: Part A, 36*(8), 1261–1272. https://doi.org/10.1080/19440049.2019.1627001

Zhang, H., & Sablani, S. (2021). Biodegradable packaging reinforced with plant-based food waste and by-products. *Current Opinion in Food Science, 42*, 61–68. https://doi.org/10.1016/j.cofs.2021.05.003