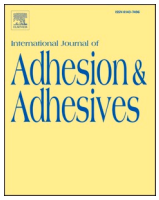
International Journal of Adhesion & Adhesives 150 (2026) 104386



Contents lists available at ScienceDirect

International Journal of Adhesion and Adhesives

journal homepage: www.elsevier.com/locate/ijadhadh





Surface engineering and coating strategies for biaxially oriented polypropylene (BOPP) films: performance, processability, and environmental trade-offs

Paula Fernanda Janetti Bócoli [a,b], Talita Braga Brito Nogueira [b], Amanda Alves Domingos Maia [b], Luís Marangoni Júnior [a,*]

[a] Universidade Estadual de Campinas (UNICAMP), School of Food Engineering, Department of Food Engineering and Technology, Campinas, 13083-862, Brazil
[b] Packaging Technology Center, Institute of Food Technology, Campinas, 13070-178, Brazil

ARTICLE INFO

Keywords:
Barrier properties
Metallization
Coatings
Sustainable materials
Surface treatment

ABSTRACT

Biaxially oriented polypropylene (BOPP) films are widely used in packaging for their transparency, low cost, and strong mechanical properties, but they suffer from a notable drawback: poor gas barrier performance, especially to oxygen. To address this limitation, a range of coating strategies has been pursued, from traditional inorganic layers to more sustainable solutions such as renewable-source coatings, barrier varnishes, functional adhesives, and nanocoatings, aimed at improving protection against oxidation and moisture loss in food applications. Surface treatments (plasma, flame, corona) and adhesion promoters are commonly employed to enhance coating bonding and thereby lower oxygen transmission rate (OTR) and water vapor transmission rate (WVTR). Coating effectiveness is governed by key factors including thickness and uniformity, adhesion strength, relative humidity sensitivity, and processing conditions, underscoring the ongoing need for optimized high-barrier multilayer films. This review critically examines these coating technologies and surface treatments, evaluates the principal performance determinants and characterization methods, and outlines challenges and future research directions, with emphasis on food-safety compliance, regulatory considerations, and sustainable, circular economy aligned solutions, to guide development of optimized high-barrier BOPP multilayer systems.

1. Introduction

Flexible plastic packaging represents one of the most widely used solutions in the global market due to its versatility, lightness, and efficiency in terms of cost and logistics [1]. With applications ranging from the food sector to hygiene, cleaning, pharmaceutical, and cosmetic products, this type of packaging stands out for its ability to protect the product, extend its shelf life, and reduce losses throughout the supply chain, in addition to meeting consumers' needs for convenience and practicality.

Among the materials most used in the food packaging segment, BOPP (biaxially oriented polypropylene) stands out, combining properties such as excellent transparency, gloss, rigidity, mechanical strength, and machinability, as well as providing a good moisture barrier. These characteristics ensure adequate protection and visual appeal, being fundamental for the preservation and enhancement of products at the point of sale. Although they exhibit excellent properties, BOPP films have a low oxygen barrier, an important requirement for the preservation, especially of foods that are sensitive to oxidation, and to prevent the growth of aerobic microorganisms [2,3]. This limitation is generally overcome by incorporating inorganic materials, such as aluminum, through a vacuum deposition process of a thin layer of evaporated aluminum onto a polymeric substrate, known as metallization [4]. Metallization is a robust strategy to enhance barrier properties, providing a significant increase in protection against the permeation of gases (such as oxygen), water vapor, and UV light.

The flexible plastic packaging market is highly impacted by the growing movement towards more sustainable solutions, driven by both regulations and pressure from consumers and major brands to reduce environmental impacts. Although metallization is a widely used technology, it has increasingly been the focus of studies aimed at its replacement, since the recycling of multilayer films composed of dissimilar materials, such as polymers and aluminum, is technically and economically challenging. This is mainly due to the differences in

* Corresponding author.
E-mail address: luismj@unicamp.br (L. Marangoni Júnior).

https://doi.org/10.1016/j.ijadhadh.2026.104386
Received 17 March 2026; Received in revised form 1 May 2026; Accepted 8 June 2026
Available online 10 June 2026
0143-7496/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

physicochemical properties and the thermal immiscibility of these materials, which hinder conventional recycling processes [2,3]. Recycled materials obtained from metallized films have a darker color, and the presence of aluminum generates critical points in the process, due to the greater need for cleaning the filters to remove residues, which compromises productivity and increases maintenance costs.

In this context, research and development of new materials and processes are gaining prominence, aiming to align industrial competitiveness, resource efficiency, and greater circularity in the life cycle of flexible packaging in the world. Emerging coating systems, ranging from water-based polymers and bio-derived formulations to organic-inorganic hybrid networks and nanostructured layers, offer promising avenues. These advancements aim not only to expand the functional capabilities of BOPP films but also align with global sustainability goals, enabling monomaterial structures, improving recyclability, and reducing dependence on energy-intensive or solvent-intensive processes.

Varnishes with barrier properties have been the subject of increasing development, to enhance the use of monomaterial films or films compatible with the recycling chain, incorporating barrier functionality through the application of these coatings. Carboxymethylcellulose (CMC) and cellulose are being studied as alternative coatings seeking mechanical properties, oxygen and oil barrier properties, and antimicrobial properties [5]. Polysaccharides, such as pectin, lipids, and proteins are also renewable sources whose potential for coatings is currently being studied [6,7]. The incorporation of inorganic nanoparticles, such as zinc, silver, and silicon oxides, and nanocomposites, such as PLA + CNC, chitosan + nanoclay, and chitosan + CNF [8,9] also comprise the alternative coatings for polymeric materials.

Among the synthetic materials with potential for application as coatings, poly(vinyl alcohol) (PVOH) stands out. PVOH is widely recognized for its low oxygen permeability, good thermal resistance, excellent adhesive properties, and resistance to organic solvents, characteristics that make it particularly attractive for use in barrier coatings. In addition, PVOH is recyclable and compatible for food contact, expanding its application potential. However, its high sensitivity to water represents a significant limitation when used alone as a packaging material, restricting its use under certain conditions [10,11].

The literature predominantly reports empirical findings on successful approaches, ranging from plasma treatments to multilayer nanocoatings, thereby enabling the identification of key research gaps and persistent unmet needs in the field, such as hydrophobic recovery, aging effects, and the potential for surface damage or haze formation. Furthermore, although plasma-based methods consistently improve adhesion and mechanical properties, recent reviews indicate that their capacity to enhance gas and moisture barrier performance remains limited [12,13]. Considering these aspects, this review aims to provide a comprehensive overview of barrier coating technologies for BOPP films, covering coating types, application methods, surface-preparation requirements, and recent advances and studies toward more sustainable and recyclable solutions. Regulatory considerations and future challenges associated with the development and implementation of these coatings are also examined.

2. Polypropylene films

Polypropylene (PP) is one of the most widely used materials globally for packaging, especially in the food sector [14–16], owing to its low cost and excellent processability across various molding techniques [17]. In comparison to other petroleum-based plastics, PP offers superior mechanical strength, thermal stability, and enhanced processability [18,19]. PP is a low-density polymer (0.90 g/cm^3) with a high melting point and rigidity. It exhibits excellent chemical resistance to acids, alcohols, and bases, along with flame retardancy, optical transparency, dimensional stability, and high recyclability potential [17,19,20]. Chemically, PP is a polyolefin composed of repeated propylene units (C_nH_{2n}), with a semicrystalline, linear structure and minimal unsaturation [4].

Discovered in 1954 by Giulio Natta, PP is produced via addition polymerization of propylene monomers. Its properties can vary depending on processing conditions, molecular weight, and molecular weight distribution [16,17]. Commercially viable PP for packaging is produced using a specific catalyst, most notably the Ziegler-Natta catalyst, which controls the stereoregularity of the polymer chains by aligning the monomers to form isotactic structures (regular arrangement of methyl groups either above or below the chain plane) [4].

Depending on its composition, PP can be classified as a homopolymer, comprising only propylene monomers, or as a copolymer, formed from polymerizing propylene and ethylene simultaneously. Copolymerization disrupts the regularity of the polypropylene chain, reducing crystallinity uniformity. Compared to homopolymers, copolymers generally exhibit improved impact resistance, lower melting points, and increased flexibility. Conversely, homopolymers are used in industry due to their high stiffness at room temperature, higher melting points, lower transparency, and reduced impact resistance [17].

A key application of commercial PP, with a global market exceeding 80 million tons, is the production of rigid packaging such as bottles, lids, trays, and flexible films, including mono- or biaxially oriented films, woven fabrics, and filaments [4]. These are manufactured through processes such as injection molding, extrusion, blow molding, and thermoforming. Of the total production, over 30% is allocated to film manufacturing, driven primarily by the packaging industry [21].

The production of PP films, like most polymers, involves multiple stages starting with polymerization. After obtaining the polymer, it undergoes extrusion, where the material is melted and forced through a flat die to form a continuous sheet, which is rapidly cooled. This process, known as casting, yields films with superior thickness uniformity and transparency [22,23]. Alternatively, in the blown film process, the polymer is extruded through a circular die and expanded with air, forming a bubble that is cooled and collapsed into tubular film. This method provides enhanced mechanical strength, but less uniform thickness compared to casting [24,25].

During film fabrication, polymer chains are initially arranged in a relatively random orientation. When stretched through a process known as orientation, the chains align along the stretching direction, significantly modifying the film's physical properties. Such properties include increased tensile strength, reduced tear (at machine direction – MD), improved puncture resistance, enhanced gloss, transparency, water and oxygen barrier performance, and increased stiffness [24–26].

Biorientation further enhances film properties by stretching the material in two perpendicular directions: the machine direction (MD) and the transverse direction (TD) [27]. For PP, the resulting film is termed BOPP (biaxially oriented polypropylene), widely used in flexible food packaging, labels, and protective films. Biorientation is achieved mainly via two methods: the tenter frame, where the film is stretched longitudinally and transversely using pinched clamps during heating, and the double bubble tubular film (DBTF) process, where extruded tubular film is inflated, heated, and continuously stretched in both directions. The choice depends on the desired properties, production efficiency, and application, with DBTF being more cost-effective [26]. Typical stretching ratios for BOPP production are approximately 5 in MD and 9 in TD; ratios below these, result in non-uniform thickness, while higher ratios increase the risk of film breakage and reduce productivity [20,25]. Fig. 1 illustrates the process flow of BOPP film manufacturing. Finally, after biorientation, the film undergoes thermal stabilization in heating tunnels and is then cooled, and the surface is treated to improve adhesion of inks, adhesives, or coatings. The film is then wound into rolls, which vary in size depending on market requirements.

Coextrusion is also an important application for BOPP films, being a widely used technological solution in flexible packaging. Coextrusion is the simultaneous processing of different polymers to produce a multilayer material that combines their distinct properties with adequate

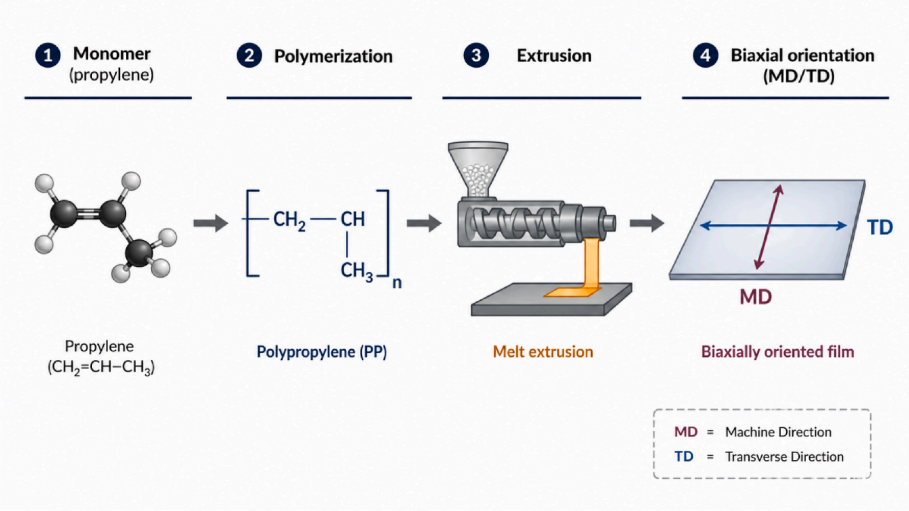


Fig. 1. Schematic diagram of BOPP film production (Font: author).

interlayer adhesion [28]. This process reduces the need for film lamination, contributing to greater process efficiency and potential cost reduction [29]; however, it can present environmental problems due to the difficulty of dissociating the constituent polymers at the end of their useful life for recycling [28]. From a processing point of view, the production of coextruded BOPP films involves controlling the material distribution at the die exit, thickness uniformity, and temperature of each layer [28].

Regarding barrier properties, BOPP films exhibit high resistance to water vapor transmission rate (WVTR) but limited barrier performance against oxygen (OTR). This behavior is primarily due to the nonpolar nature of the polymer chains, which directly influences their interaction with permeant molecules [26,30]. Achieving the desired barrier performance in BOPP films is possible through surface treatments such as coating, metallization, incorporation of nanocomposites, or multilayer lamination structures [31]. Overall, the barrier effectiveness depends not only on the polymer's intrinsic structure but also on factors such as film thickness, surface conditions, ambient humidity, and the method of coating application [32].

BOPP films are widely used in the packaging industry, especially for food applications. To meet specific barrier requirements, various configurations are employed, including metallization, lamination, and surface coatings to facilitate sealing. Common applications include packaging of snacks, powders, confections, fruits, and vegetables, helping to preserve freshness and extend shelf life. Transparent films are often preferred for their clarity, moisture resistance, and printability, adding value at points of sale. Metallized films provide superior barriers against light, oxygen, and moisture, making them suitable for premium packaging of snacks, confections, and powdered products. Film thickness options range from 15 to 30 μm for labels and overwraps, to 30–40 μm for pouches and bulk food packaging, ensuring mechanical strength and stability.

The oxygen barrier performance is one of the key parameters for packaging applications based on BOPP films, being strongly influenced by the presence and type of surface coating. Uncoated BOPP films exhibit relatively high oxygen permeability (OTR), typically in the range of 2000–2500 $cm^3\ m^{-2}{\cdot}24\ h^{-1}$, which limits their use in oxidation-sensitive products, such as lipid-rich foods. In this context, different coating strategies have been explored to reduce gas permeation, including the application of inorganic, hybrid, and multilayer structures. Among the most widely used approaches are aluminum metallization, metal oxide coatings such as AlO_x, and material modification through the incorporation of nanophases, such as nanocellulose. These solutions enable significant reductions in the oxygen transmission rate, reaching typical values of 20–50 $cm^3\ m^{-2}{\cdot}24\ h^{-1}$ for metallized films, 50–100 $cm^3\ m^{-2}{\cdot}24\ h^{-1}$ for AlO_x-coated films, and 10–30 $cm^3\ m^{-2}{\cdot}24\ h^{-1}$ for systems containing nanocellulose [33], highlighting the fundamental role of surface engineering strategies in enhancing the barrier performance of BOPP films.

3. Barrier coatings

3.1. Surface treatments of polypropylene films

Polypropylene (PP) has a chemically inert, non-porous surface with low surface energy, which hinders adhesion of coatings. Various surface treatments (Fig. 2) are employed to introduce polar groups and increase the hydrophilicity of PP, thereby enhancing its adhesion to coatings or improving its surface properties [34]. Table 1 shows the surface treatments of polypropylene and BOPP films and their influence on physicochemical and functional properties.

3.1.1. Plasma treatment

Surface treatment via plasma involves ionizing gas (such as air, nitrogen, argon, oxygen, nitrous oxide, helium, water vapor, carbon dioxide, methane, or ammonia), generating a mixture of ions, electrons, and neutral particles. Exposure of the material to this ionized gas induces physical and chemical surface reactions, altering surface properties. Plasma treatment renders BOPP surfaces polar by incorporating ionized oxygen molecules that bond to surface molecules, enhancing adhesion. Electron bombardment can occur at velocities up to 100 times higher than corona treatment, leading to greater surface erosion and forming stronger chemical bonds [34,52]. Several factors influence the type and concentration of reactive species generated, including plasma source, voltage, pressure, electrode configuration and distance, treatment duration, and reactive gas type [53]. The nature of chemical reactions between plasma reactive species and BOPP depends on the gas used, as each gas produces a distinct plasma with different surface effects [34].

Plasma can be generated under different temperature and pressure conditions, classified as thermal or non-thermal (cold) plasma. Thermal plasma requires higher pressure and power, maintaining a thermodynamic equilibrium among species. Non-thermal plasma, however, does not inherently reach equilibrium and can be generated using various energy sources capable of ionizing gases and producing reactive species, including electric and magnetic fields, thermal, electrical, optical, radioactive, and X-ray sources [53].

Plasma technology is extensively applied to PP and serves as an

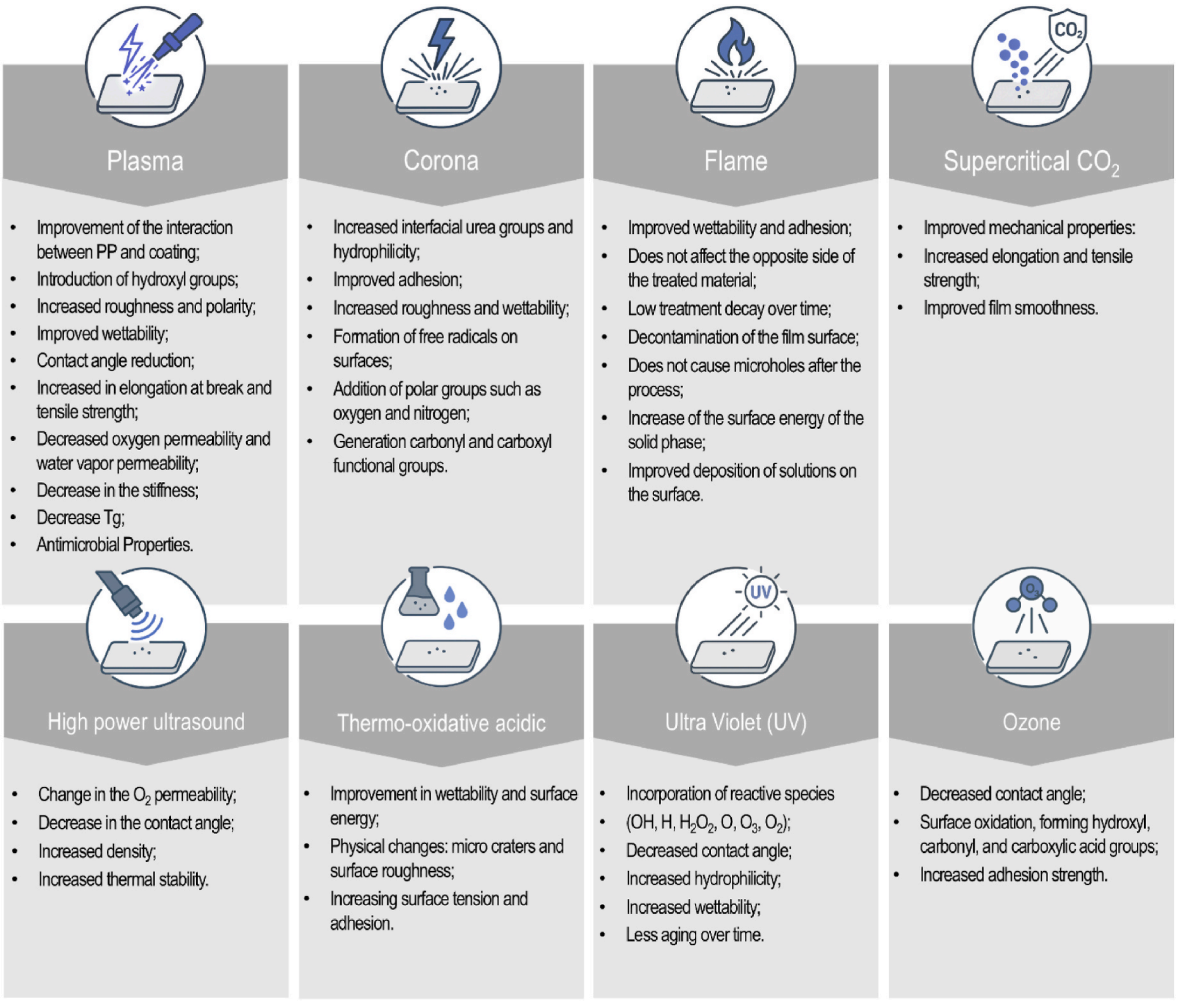


Fig. 2. Properties of polypropylene modified by various surface treatments (Font: author).

effective pre-treatment for producing bi-layer films, facilitating the adhesion of biodegradable natural coatings onto synthetic polymer layers, often resulting in films with reduced thickness [37]. It also enhances hydrophilicity through exposed hydroxyl groups, improving wettability and decreasing contact angles, thus promoting better adhesion of coatings such as SiO_2 and TiO_2 nanocoatings (Sun et al., 2025) or chitosan-resveratrol nanocoatings [36]. Additional effects include increased surface roughness, improved bonding capacity, greater elongation at break, higher tensile strength, reduced water vapor permeability, increased moisture transmittance, and decreased stiffness and glass transition temperature (T_g) [35–37,39].

Plasma treatment offers several advantages, such as ease of generation and control, operation at atmospheric pressure, low cost, suitability for inline processing, and environmental friendliness [37]. However, limitations exist, including the dependence on polymer type, which influences treatment efficacy, and the limited penetration depth of plasma into the polymer matrix, requiring evaluation of whether the desired modifications reach deeper layers and the reverse side of the film [39]. Techniques such as diffuse coplanar surface barrier discharge can improve surface modification on both exposed and unexposed sides, evidenced by the presence of hydroxyl (OH) groups and decreased contact angles [38].

3.1.2. *Corona treatment*

Corona discharge is a specific form of plasma generation, characterized by occurring under atmospheric pressure, usually in air. This treatment involves applying continuous high-voltage, high-frequency electric discharge to the surface of polymer materials such as PP, PET (polyethylene terephthalate), and PA (polyamide) [54], thereby increasing surface energy. The high-voltage process induces molecular chain scission and generates free radicals on the film surface, which can react with atmospheric oxygen to form polar oxygen- or nitrogen-containing groups, enhancing surface wettability. Simultaneously, gas molecules dissociate into charged species under the high voltage, bombard the surface, and increase surface roughness, preparing the film for better adhesion of coatings or other materials [43].

Corona treatment offers advantages such as simple operation, easy control, high speed, and short processing time [43]. In BOPP, this treatment has demonstrated multiple benefits, including improved adhesion, increased wettability, surface roughness, and hydrophilicity through the introduction of polar groups such as carbonyls, carboxyls, and nitrogenous groups [41–45]. Enhanced adhesion facilitates the production of printed and coated films. For example, grafting polyacrylic acid (PAA) onto the BOPP surface with hydroxyl groups modified by corona treatment improved the attachment of SiO_2 and TiO_2 nanocoatings and enhanced water-based ink adhesion and printability precision [55]. Additionally, corona-treated PP increased interface hydrophilicity with polyurethane (PU), promoting chemical interactions, increasing urea bond formation, and improving PU adhesive adhesion [41]. Corona treatment is a simpler and less controlled form of atmospheric plasma, while plasma, in a broader sense, offers greater precision, versatility, and control over surface modification.

Table 1
Surface treatments of polypropylene and BOPP films and their influence on physicochemical and functional properties.

Application	Conditions	Results	Reference
Plasma			
BOPP film	Forward power: 1.5 W	Introduction of hydroxyl groups Increased surface roughness and polarity Increase in moisture transmittance of treated BOPP film	[35]
PP foil	Forward power: 200W Oxygen pressure: 50 Pa Exposed to late oxygen afterglow: 60 s.	Improvement of the interaction between PP and chitosan Improved hydrophilicity and homogeneity Introduction of hydroxyl groups Decreased oxygen permeability Improved antimicrobial and antioxidant properties	[36]
PP film	Working gas: air Voltage: 14 kV Frequency: 20 kHz Speed of 3.6 m/min	Introduction of hydroxyl groups Improved wettability Increased surface roughness and bonding capacity Increased in elongation at break and tensile strength Decrease in water vapor permeability	[37]
PP film	Forward power: 350W – 375 W Plasma treatment time: 2 – 10 s	Contact angle reduction	[38]
PP film	Forward power: 350W Plasma treatment time: 5 s	Decrease in the stiffness Decrease in Glass Transition Temperature (Tg)	[39]
PP non-woven material	Plasma fluorination: Plasma treatment time: 0 – 25 min Pressure 50 - 150 Pa Gas flow rate: 5 - 15 $cm^3\ s^{-1}$ Discharge current: 20 mA	Increase in hydrophobicity Increase in the roughness Antimicrobial Properties (*Staphylococcus aureus* and *Escherichia coli)*	[40]
Thermo-oxidative acidic			
PP film	t: 2.5–25 min T: 90 ± 1 °C Concentration solution (mol/dm^3): CrO_3: 0.36; H_2SO_4: 7.2; H_3PO_4: 6.6	Improvement in wettability and surface energy Physical changes: micro craters and surface roughness increasing surface tension and adhesion	[1]
Corona			
PP film	Voltage:10 kV Frequency: 4.5 MHz Distance: 1.5 cm	Increased interfacial urea groups and hydrophilicity Improved adhesion between PP/PU (25-53% moisture content)	[41]
BOPP microporous membrane	Power: 300 W - 500 W Times:10 s – 300 s	Generation carbonyl and carboxyl functional groups Conversion of the Hydrophobic BOPP Membrane to Super Hydrophilic	[42]
BOPP film	Corona Treatment Power: 2 -3 kW Corona Cycles: 3-7 Corona processing speed: 15 m/min	Formation of free radicals on surfaces Addition of polar groups such as oxygen and nitrogen Increased surface roughness Increased hydrophilicity	[43]
BOPP film	Speed: 1.44 m/min Air-gap between the electrode and film: 3 mm Corona energies: 15.3, 38.2 and 76.4 kJ/m^2 With and without the vapor of AAc monomer Film aging: 1, 7 and 90 days	Increased roughness and hydrophilicity Increased wettability even after aging (90 days) Improved adhesion	[44,45]
PP film PET film PP/PET multilayer film	Atmospheric pressure Maximum output power: 8 kW Operating power: 3 kW Surface tension: 55 dyn/cm.	Reduced the incorporation of α-tocopherol Impaired the control of α-tocopherol release	[46]
Oxidizing flame			
PP capsules	Compressed air (oxidizer); Liquid propane (fuel) Substrate-to-flame distance: 14.0 mm (frontal); 15.0 mm (side) Flame contact time: 0.05 s Rotation speed of capsule: 470 rpm Flame power: 6938 kJ h^{-1}	Increase of the surface energy of the solid phase Improved deposition of solutions (pullulan and a silicon-dioxide precursor) on the surface of the PP capsules	[47]
BOPP film	Flame power: 170 W/cm^2 Surface área: 320 W/cm Speed: 150 m/min		[48]
Supercritical CO_2			
PP monooriented film	8, 12 and 16 Mpa; 60 °C; 6 h	Improved mechanical properties: Increased elongation (40%) and tensile strength (30%) Improved film smoothness	[49]
High power ultrasound			
BOPP coated with acrylic/ polyvinylidene chloride	Time: 2, 4 and 6 min Amplitude: 50-100% Power: 600 W Frequence: 20 kHz, 12–260 μm Diameter probe: 12.7 mm	Increased thermal stability	[50]
BOPP coated with acrylic/ polyvinylidene chloride	Time: 2, 4 and 6 min Amplitude: 50-100% Temperature: Power: 600 W Frequence: 20 kHz, 12–260 μm	Reduction in the contact angle Increased hydrophilicity	[51]

PP: Polypropylene; BOPP: Biaxially oriented polypropylene; PU: Polyurethane; PET: Polyethylene terephthalate; AAc: Acrylic acid.

3.1.3. Flame treatment

Flame treatment is an important technique to enhance the surface energy of polymers such as BOPP. It involves combusting fuel, such as methane, propane, or butane, with an oxidizer, typically air, resulting in an exothermic reaction that dissociates free oxygen atoms which bombard the material's surface [34,56]. The polymer surface is activated through degradation of free radicals at the tertiary carbon of the PP chain. This oxidative process occurs in several stages, starting with C-H bond cleavage at high combustion temperatures (~1700–1900 °C) and subsequent insertion of oxygen-containing groups, increasing hydrophilic regions that facilitate coating adhesion [57,58]. The oxidation of methyl groups ($–CH_3$) into $–CH_2OH$ groups after flame treatment significantly impacts properties such as wettability and adhesion, making this process highly relevant [48,57].

Achieving optimal adhesion involves maximizing the generation of specific chemical groups on the polymer surface. Flame treatment can oxidize the surface in a controlled manner, forming an ultra-thin layer roughly 5–10 nm thick [59] An important parameter is the treatment zone depth, which correlates with the exposure duration [58]; increasing the number of passes with the flame elevates oxygen-containing groups and penetrates deeper into the surface.

Advantages of flame treatment include its versatility across different materials such as bottles and films, high treatment intensity, no effect on the opposite side of the substrate, low long-term degradation, surface decontamination, absence of microvoid formation, and cost-effectiveness [34,58]. Treated BOPP becomes more oxidized after water washing, more hydrophilic, and more stable compared to corona-treated films, with no formation of low molecular weight oxidized species [56].

However, high temperatures during flame treatment can damage the surface due to heat accumulation, potentially reduce transparency, impose productivity limitations, and require constant process monitoring [34]. The distance between the flame and BOPP surface influences the oxygen level: greater distances correlate with lower oxygen content on the surface. Other factors affecting the process include flame intensity (gentle or strong), air-to-gas ratio, total flow rate, and contact time with the flame [60].

3.1.4. Other treatments

In addition to the treatments, other surface modification methods already used in food processing can be applied to polymers such as PP and BOPP include thermo-oxidative acid treatment, supercritical CO_2, and high-power ultrasound. Fig. 3 presents the surface of BOPP before and after the application of various surface treatments.

Thermo-oxidative acid treatment involves converting hydrogen atoms on the surface of the film into polar groups using a mixture of chromic, sulfuric, and phosphoric acids at elevated temperatures for short durations. This process grafts polar groups such as hydroxyl, carboxyl, and carbonyl onto the surface by cleaving covalent bonds in the carbon chain [1,61]. It enhances wettability and adhesion, induces physical changes like microcraters and increased surface roughness, and increases surface area and surface tension [61]. The effectiveness depends on factors such as acid type, oxidant concentration, treatment time, temperature, and polymer nature [1,61].

Supercritical CO_2 is a fluid characterized by temperature and pressure above its critical point (31.1 °C and 7.38 MPa), where phases become indistinguishable. Widely studied as a solvent alternative and for environmental remediation [49,62], supercritical CO_2 has been employed to expand PP and produce foams [63,64]. In mono-oriented PP films, supercritical CO_2 treatment (e.g., 60 °C for 6 h at 8–16 MPa) improved mechanical properties, with over 40% increase in elongation at break and 30% in tensile strength, without altering appearance, optical properties, or density. These effects are attributed to γ-phase formation, increased free volume, and chain relaxation within the polymer [49].

High-power ultrasound can induce mechanical and chemical effects such as cavitation, modifying density, mechanical properties, and permeability [65–68]. Ultrasonication for 6 min at 100% amplitude reduced oxygen permeability and contact angles in coextruded BOPP (90.8° to 80.6°) and acrylic/polivinylidene chloride-coated BOPP (86.7° to 74.9°) [69]. In recent studies, ultrasound treatments improved thermal stability and surface crystallinity, with optimal results observed at 2–6 min and 50–100% amplitude, attributed to formation of crystalline agglomerates on the surface [50].

Ultraviolet (UV) radiation treatments on polymer surfaces have been increasingly studied in recent years. In PP, Du et al. (2025) investigated the synergistic effects of oxygen radicals (O) and ozone species (O_3) using vacuum ultraviolet photodissociation reactive species supply (VUV PRS) on BOPP surfaces. This method enables the selective and quantitative delivery of specific reactive species such as OH, H, H_2O_2, O, O_3, and O_2 through UV photodissociation at 172 nm of H_2O, CO_2, or O_2 molecules in a gas mixture. The incorporation of these reactive species reduced the contact angle on PP surfaces, thus increasing the film's hydrophilicity [70].

Although no significant changes in surface roughness were observed on injection-molded PP parts, Wanke et al. (2012) reported a substantial decrease in contact angle over the treatment period, dropping from 98° to 58° after 20 min. The enhanced wettability was attributed to possible superficial chemical modifications induced by UV exposure. The aging of PP samples treated with UV and plasma was monitored over 0, 3, 7, 14, 21, and 28 days. After seven days, the contact angle of UV-treated samples increased by approximately 4°, whereas plasma-treated samples exhibited a larger increase of around 30° [71].

Exposing PP films to UV light combined with ozone increased surface energy, improving wettability and adhesion performance. This enhancement was linked to the formation of low molecular weight oxidized materials leading to surface densification [72]. Another study using ozone in conjunction with UV demonstrated improved coating coverage and adhesion of cellulose nanocrystal (CNC) layers on PP films,

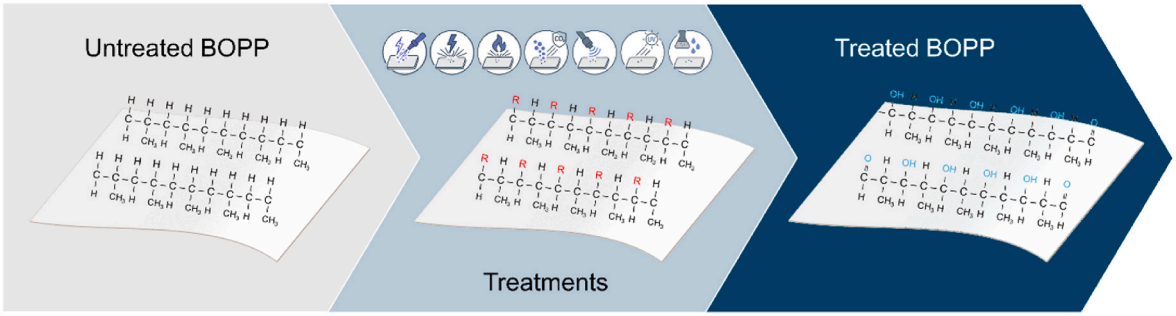


Fig. 3. BOPP surface before and after the application of different surface treatments (Font: author).

resulting from surface oxidation of polymer chains and the introduction of polar groups. Surface roughness of the PP film increased following ozone-UV treatment, and the contact angle decreased significantly, from 95.8° to 78.5°, and further down to 13° with CNC addition, indicating increased surface hydrophilicity [73].

Ozone treatment promotes surface oxidation of PP films and fibers, generating hydroxyl, carbonyl, and carboxyl groups, which can form covalent bonds with coatings such as hydroxylated ZnO nanoparticles. This process increased the adhesion strength of ZnO nanoparticles by approximately 1.9 times compared to untreated PP, demonstrating enhanced nanoparticle fixation [74].

Modifying the surfaces of PP is fundamental to enabling efficient functionalization, especially when subsequent layers are to be incorporated. These treatments favor the interaction between the polymeric substrate and the applied materials by increasing surface energy, incorporating polar groups, and improving wettability and roughness. As a result, the success of applying functional coatings depends on these prior surface modifications. In this scenario, it is essential to consider the various techniques for depositing barrier coatings on PP films, as these methods must be compatible with the modified surface to ensure uniform coverage, robust adhesion, and improved performance.

Table 2 shows that selecting a surface modification technique requires evaluating efficiency, cost, and process control. Plasma and flame oxidizing techniques offer functionalization and adjustability, while corona and conventional flame techniques provide simplicity and scalability. UV, ozone, and ultrasound methods allow controlled but less intense modifications. Treatment stability is essential for long-term performance. Ultimately, the most suitable technique is determined by the required surface properties and compatibility with industrial polymer film processing.

3.2. Techniques for applying barrier coatings to polypropylene films

Barrier coatings are functional thin film layers that can be applied to polymeric substrates to improve their end-use properties. Coating technology has been proposed as a promising strategy to broaden the application range of mono-material films and, in turn, reduce the need for multilayer packaging [81]. Coating applications can be done using different techniques and under different conditions, always seeking process optimization and improved properties, mainly barrier properties, in the polymer. According to the characteristics of the methods, they can be classified/divided into physical vapor deposition (PVD) methods, chemical vapor deposition (CVD) methods, plasma-enhanced techniques, and multilayer coating methods (layer by layer – LBL) [82]. Table 3 shows the different coating techniques applied to BOPP films and their characteristics.

3.2.1. Physical Vapor Deposition methods (PVD)

In vacuum deposition processes, generally only one inorganic material is deposited, as the coating material is heated and subsequently condensed onto the substrate surface. An important characteristic of this technique is related to obtaining thin layers on the material. The reduced pressure lowers the energy required to melt the material and significantly minimizes the incorporation of gaseous atoms into the coating, are important advantages. Compared with other techniques, vacuum deposition enables high deposition rates and the production of extremely pure coatings [82,87,88].

Sputtering deposition is a PVD technique in which atoms are ejected from a solid target material by momentum transfer from energetic ions generated in plasma. This non-thermal vaporization process occurs when accelerated gas ions, typically argon, collide with the target surface, producing a cascade of atomic collisions that result in the ejection of surface atoms. The sputtered atoms then condense onto a substrate, forming a thin, uniform coating. Because the energy of the bombarding particles is primarily converted into heat near the surface, temperature control is critical to prevent target damage or substrate overheating. Sputtering offers several advantages over thermal evaporation, including better film adhesion, precise thickness control, and the ability to deposit alloys and compounds with uniform composition [82,87]. This technique, particularly aluminum metallization, is widely used in the packaging industry to enhance the barrier properties of BOPP films. However, its performance is strongly influenced by the presence of microstructural defects such as pinholes and microcracks, which act as preferential pathways for gas permeation [89]. As a result, alternative techniques such as atomic layer deposition (ALD) and plasma-enhanced chemical vapor deposition (PECVD) have gained increasing attention due to their ability to produce highly uniform and pinhole-free coatings with precise thickness control [90].

3.2.2. Chemical Vapor Deposition (CVD)

Chemical vapor deposition is a thin-film deposition technique in which one or more volatile precursors are introduced into a reaction chamber, where they chemically react or decompose on a heated substrate surface to form a solid material. The process takes place in the gas phase and results in the deposition of a dense, uniform, and adherent coating composed of metals, oxides, nitrides, carbides, or other compounds. CVD can be carried out under various conditions: atmospheric, low, or plasma-enhanced pressures, allowing precise control over film composition, morphology, and thickness. Unlike vacuum deposition, CVD does not require high-vacuum systems, although it may generate volatile and potentially toxic by-products that require appropriate handling. The high kinetic energy of the reacting species can increase substrate temperature, and interactions with precursor atoms may cause scattering of evaporated species. Because of this, care must be taken to control the interfacial reactions between coating and substrate and between substrate and gaseous reaction products. These effects can result in surface roughening, atomic or molecular penetration into the substrate, pinhole formation, and unwanted chemical reactions with residual gases. Nevertheless, CVD can achieve relatively thick coatings, up to the centimeter scale, and because deposition is not limited to line-of-sight regions, it allows for uniform coating of complex three-dimensional structures, including voids and peaks [82,83,88].

3.2.2.1. Plasma-Enhanced Chemical Vapor Deposition (PECVD). Plasma-enhanced chemical vapor deposition is a variation of the conventional CVD process, in which plasma is used to activate the chemical deposition reactions. In this method, gaseous precursors are introduced into a chamber where plasma is generated, usually by radio frequency (RF) discharge or microwaves, promoting the ionization and dissociation of the reactant molecules. The main advantage of PECVD is that it allows deposition to occur at significantly lower temperatures than in thermal CVD, since the energy needed to break the chemical bonds is supplied by the plasma and not just by heating the substrate. This makes the process especially useful for coatings on polymers, heat-sensitive materials, and flexible substrates. Films obtained by PECVD can be oxides, nitrides, carbides, polymers, or hybrid structures, exhibiting good uniformity, adhesion, and thickness control. However, the process requires strict control of plasma parameters (power, pressure, gas flow, and temperature) to avoid damage to the substrate and ensure coating reproducibility [91].

3.2.3. Atomic Layer Deposition (ALD)

Atomic layer deposition (ALD) is a thin-film growth technique in which the substrate is exposed to sequential pulses of gaseous precursors that undergo self-limiting reactions directly at the material surface, enabling precise control of film thickness and composition. The process can be conducted at relatively low temperatures (e.g., around 80 °C), making it particularly suitable for heat-sensitive substrates such as BOPP films, without reaching their melting point. Moreover, ALD does not compromise the intrinsic mechanical properties of the substrate, such as tensile strength and elongation, and may even lead to slight

Table 2
Comparison of different surface modification methods applied to polymers.

Treatment	Process principle	Typical conditions	Surface effects	Advantages	Limitations	Inline integration	Relative cost	Process control	Industrial scalability	References
Plasma (low and atmospheric pressure)	Electrical discharges generate reactive species (ions, radicals, UV radiation)	Low or atmospheric pressure; gases such as O_2, Ar; controlled power	Introduction of polar groups (–OH, –COOH), increased surface energy and roughness	High control, versatile, uniform treatment	High cost (low-pressure systems), surface aging	Moderate to high	Medium to high	Excellent	High (especially atmospheric plasma)	[53,61,71,75–78]
Corona	Dielectric barrier discharge in ionized air	Atmospheric pressure; high voltage; air as medium	Surface oxidation, increased wettability	Low cost, easy inline integration	Limited treatment depth, lower uniformity	Excellent	Low	Moderate	Very high (widely used industrially)	[54,56,61,79]
Flame	Controlled combustion generates reactive species and heat	Combustible gases (propane, butane); open atmosphere	Strong oxidation, increased polarity and slight roughness	Fast, efficient, low cost	Limited control, thermal damage risk	High	Low	Low to moderate	High	[56,57,60,80]
Ozone	Oxidation by O_3 and derived reactive species	Atmospheric or controlled environment; ozone presence	Introduction of oxygen-containing groups, increased surface energy	Clean, non-contact process	Low penetration depth, possible material degradation	Moderate	Low to medium	Moderate	Moderate	[61,70]
UV	UV radiation generates free radicals and promotes photo-oxidation	UV exposure in presence of O_2	Surface chemical modification, slight morphological changes	Dry and controllable process	Limited modification depth	Moderate	Low	High	Moderate	[61,71,72]
UV/Ozone	Combined UV radiation and ozone produce synergistic oxidation	Simultaneous UV and O_3 exposure	Significant increase in functionalization and adhesion	More effective than individual methods	Possible over-degradation	Moderate	Low to medium	High	Moderate	[70,72]
Supercritical CO_2 ($scCO_2$-based process)	Supercritical CO_2 acts as a diffusion medium enabling modification	High pressure and temperature (supercritical state)	Physical and structural changes, enhanced diffusion and polymer chain rearrangement	Deep penetration, environmentally friendly	Expensive equipment, severe conditions	Low	High	High	Low to moderate	[49]
High power ultrasound	Ultrasonic waves induce cavitation and mechanical effects	Liquid medium; ultrasonic frequency	Cleaning, increased roughness, indirect activation	Simple, can be combined with other methods	Limited direct chemical modification	Moderate	Low	Low	Moderate	[50,61,69]
Oxidizing flame	Controlled combustion with excess oxygen promoting oxidative reactions	Fuel/air mixtures with oxygen-rich conditions; atmospheric	Enhanced oxidation, increased polarity and wettability, controlled surface functionalization	Better control than conventional flame, improved wettability tuning	Still involves thermal exposure, process sensitivity	High	Low to medium	Moderate	High	[47,48]

Table 3
Coating techniques applied to BOPP films.

Technique	Process type	Typical temperature	Coating type	Thickness control	Uniformity	Impact on BOPP	Main applications	Advantages	Limitations	Barrier performance (typical)	References
PVD	Physical vapor deposition	Low to moderate (<100–150 °C)	Metallic/ inorganic (Al, AlO_x)	High	High (line-of-sight)	Low to moderate (thermal/ radiative load)	Metallization, barrier	Industrially established, high throughput	Lower conformality, defect sensitivity	OTR: ~0.1–5 cc/m^2·day WVTR: ~0.1–3 g/ m^2·day	[83,84]
CVD	Chemical vapor deposition	High (≥150–300 °C)	Inorganic (SiO_2, Al_2O_3)	Moderate	High	May cause thermal degradation	Barrier (O_2, H_2O)	Dense coatings, good barrier	Not suitable for heat-sensitive polymers	OTR: ~1–10 cc/m^2·day WVTR: ~0.5–5 g/ m^2·day	[85]
PECVD	Plasma-enhanced vapor deposition	Low to moderate (50–120 °C)	Inorganic/ hybrid (SiO_x, AlO_x)	High	High (may contain defects)	Low impact	Barrier, adhesion improvement	Compatible with polymers, industrial scalability	Possible pinhole formation	OTR: ~0.1–5 cc/m^2·day WVTR: ~0.1–3 g/ m^2·day	[86]
ALD	Atomic layer deposition	Low (<100 °C)	Inorganic (Al_2O_3, TiO_2)	Very high (atomic-scale)	Excellent (conformal coatings)	Very low	Barrier, UV protection	Excellent thickness control, defect-free films	Low throughput, high cost	OTR: ~10^{-3}–10^{-1} cc/ m^2·day WVTR: ~10^{-3}–10^{-1} g/m^2·day	[85]

improvements due to the thermal exposure during processing. Owing to its self-limiting nature, the technique enables the formation of highly uniform and conformal ultrathin coatings, with the possibility of designing multilayer structures to further enhance barrier performance [92,93].

3.2.4. Multilayer coatings

Multilayer coatings constitute a promising approach for designing high-performance gas and vapor barriers, as they can be engineered to deliver specific and customizable functionalities. Multilayer films consist of two or more layers of distinct materials that are laminated together [94,95]. The primary technology to obtain multilayer coatings is the layer by layer (LbL) assembly, a manufacturing process in which oppositely charged molecules are deposited in different layers, improving the adhesion and cohesion of the structure and building the desired multi-layer barrier. As an alternative to vacuum-deposited multilayer structures, the LbL assembly technique has emerged as a leading non-vacuum approach for the fabrication of transparent, high-performance gas barrier films. The LbL method is both cost-effective and versatile, offering significant potential for producing functional thin-film coatings through electrostatic or non-electrostatic interactions. Beyond improving gas barrier properties, LbL assembly can also tailor surface characteristics such as biocompatibility, polarity, and antibacterial activity by selecting appropriate assembly materials. Moreover, this technique can be applied to substrates with various geometries and allows them to control the thickness layers in nanometer scale [30,81,95–97].

3.2.5. Other coating techniques

Other coating techniques simply consist of applying a coating solution to the surface of interest, followed by drying, known as wet methods. Immersion, bar coating, and slit coating are attractive for generating high-quality coating on polymeric substrates due to time savings and homogeneous thickness control. The main challenge is achieving a homogeneous and aligned dispersion of the coatings [97]. Spraying processes are also widely used wet methods for applying coatings to polymer films. These processes can be classified into two categories: macroscopic, in which the sprayed particles have a diameter greater than 10 μm, and microscopic, characterized by the deposition of simple molecules or atoms with diameters less than 10 μm [88].

The diversity of coating techniques highlights the wide range of processing routes available for depositing thin functional layers onto PP, offering distinct advantages in terms of morphological control, adhesion, thickness, and scalability. However, the performance of the resulting barrier system is determined not only by the deposition method but also by the intrinsic properties of the materials used to form the coating. Thus, a comprehensive understanding of the relationship between processing techniques and material selection is essential for optimizing barrier performance. In this context, some studies aim to evaluate the primary functional materials used as barrier coatings for BOPP films and assess how their physicochemical characteristics enhance protection against gases and moisture.

3.3. Functional barrier coating materials applied to BOPP films

3.3.1. Metallization

Metallization is a process in which a layer of metal is deposited under vacuum onto a substrate. In most packaging segments, the primary metal used is aluminum, however, other metals, such as copper, nickel, and silver, can also be used [4,98,99]. Metallization can be performed through a continuous process, by transfer, or by batch, which is the most applied method. The polymers used as substrates are pre-treated by flame, corona, or plasma used to promote metallization and secure aluminum bonding. The process takes place in a horizontal tubular chamber inside a cooled cylinder, under a controlled atmosphere of 2–4 $\times$ 10^{-4} mmHg maintained by a vacuum pump. This setup enables

aluminum to vaporize at lower temperatures, allowing the vapor to condense onto the film surface without interference or oxidation from air exposure.

BOPP is among the most common substrates used in metallization and the metallized films offer several advantages, providing enhanced barrier properties and reduced light transmission while maintaining a low overall thickness. The combination of film orientation and metallization properties makes these materials highly suitable for packaging applications [100]. Due to their thermal reflectivity, metallized plastics can protect packaged products from extreme temperature conditions (both heat and cold) [101], in addition to exhibiting excellent mechanical properties. The thickness of the metallized layer can influence the opacity as well as the water vapor transmission rate (WVTR) and oxygen transmission rate (OTR) of the substrate [102].

3.3.2. Metallization with oxides

The application of oxide coatings represents an effective approach to enhancing the barrier properties of polymers such as PET, OPA, PLA, and BOPP. Silicon dioxide (SiOx) and aluminum oxide (AlOx) are the most used materials [103–106], however, other oxides, such as copper oxide (CuO) and chromium oxide III (Cr_2O_3), have also been employed [107]. These oxides can be deposited in different thicknesses using vacuum-based techniques. Evaporated AlOx films are mechanically fragile, which makes them prone to cracking, a drawback compared to SiOx. In contrast, SiOx, being inorganic, is chemically inert to most substances [4].

Unlike conventional metallized films, oxide-coated substrates remain transparent while exhibiting excellent barrier performance against water vapor, gases, and organic vapors [103,106]. The oxygen transmission rate (OTR) of oxide-coated laminates is typically below 10 mL (STP) m^{-2} day^{-1}, and the water vapor transmission rate (WVTR) is below 2 g m^{-2} day^{-1}, values comparable to those of high-barrier or metallized polymers [4]. In BOPP, the application of AlOx reduces both OTR and WVTR by approximately 80-fold and 1.5-fold, respectively [106].

The deposition of SiOx coatings is performed in a vacuum chamber, where solid SiOx is sublimated by an electron beam. The generated vapor condenses onto the polymer film, which is supported by a cooled cylinder, forming a thin coating layer (40–980 nm) [4]. In the case of AlOx, metallization also takes place under vacuum conditions, where aluminum is melted and vaporized [4,104]. Reactive gases are subsequently introduced into the chamber, leading to the condensation of the oxide layer onto the polymer surface. The coating may be applied as a single or multilayer structure; in the former case, a protective varnish layer is typically required.

The barrier properties of oxide-coated films provide resistance to moisture and temperature and can be influenced by the thickness of the oxide coating [103]. Therefore, oxide-coated polymers can be used in sterilizable packaging and food packaging that requires heating. Furthermore, due to their transparency, these packages can be used for microwave-prepared foods. Polymers coated with SiOx and AlOx can also be used for self-supporting packaging (stand-up pouches) due to their rigidity, in sachets, packaging for vending machines (vertical and horizontal), in cups, tray lids, laminated tubes, among other applications [4].

3.3.3. Varnishes

Varnish coatings are widely used as an additional protective layer for polymers, coatings, and printed surfaces, providing resistance against salts and/or oxides that can attack hygroscopic products [4]. The most common types of varnishes include solvent-based, UV-curable, and water-based systems. Certain types, such as solvent-based and UV-curable varnishes, contain organic solvents like cyclohexanone, which release volatile organic compounds (VOCs) during the drying process and thus contribute to environmental pollution. In contrast, water-based varnishes use polymers as film-forming materials. Moreover, coatings produced with water-based varnishes exhibit high transparency, good abrasion resistance, and environmental compatibility. Consequently, the use of VOC-emitting varnishes has been progressively reduced, while water-based systems have become increasingly prevalent in printing applications [108].

In printed materials, the application of varnishes enhances abrasion resistance, gloss, and resistance to heat and humidity, in addition to creating special visual effects and imparting a refined finish to the product. Recent studies have demonstrated advances in the formulation of high-gloss, water-based varnishes with improved impermeability, mechanical strength, and resistance to abrasion and moisture. However, water-based varnishes may still present some drawbacks, such as slower drying times and lower adhesion to printed surfaces [108].

The evaluation of varnish adhesion to the substrate can be affected by the presence of waxes and silicones in the formulation, resulting in reduced adhesion. Furthermore, the anchorage of varnishes, inks, and adhesives may also be compromised by the presence of oils and fats, particularly when the packaging material lacks an effective barrier to oil and grease permeation [4].

3.3.4. Adhesives

Adhesion is the process by which two initially separate bodies (substrates or adherends) are joined through adhesive forces. Solid surfaces are typically bonded using an adhesive, often a liquid, that is applied between the substrates. The adhesion process involves coating or preparing a solid surface with a liquid, thereby forming a new composite structure from the combination of two substrates, with or without the use of an adhesive. The resulting structure can exhibit strength comparable to that of its individual components, as interfacial bonding develops when the materials solidify [109]. Adhesives are substances capable of joining two substrates, either of similar or dissimilar chemical nature, through adhesion and cohesion mechanisms. In plastics, intermolecular forces such as van der Waals interactions and hydrogen bonding are the primary mechanisms responsible for adhesion. In porous materials such as paper, mechanical interlocking can also play a major role in the bonding process [4,109].

A wide range of adhesives can be employed in packaging systems, including reactive adhesives (notably polyurethanes), hot-melt adhesives, water-based adhesives, pressure-sensitive adhesives (PSAs), cold-seal adhesives, and coextrusion adhesives [4]. Adhesion can also occur through direct bonding of solids under heat and pressure, as in the heat sealing of thermoplastic materials. Alternatively, adhesion may be promoted by dissolving the interface with a solvent, enabling molecular interdiffusion between the substrates [109]. Adhesives are essential components in packaging, serving multiple functions, such as:

(i) forming multilayer structures by combining different substrates (e.g., aluminum foil, metallized polypropylene or polyester films, polyethylene, polypropylene, ionomers, poly(vinyl chloride), polyesters, polyamides, paper, and paperboard);
(ii) shaping packaging geometries (e.g., forming and sealing cartons, corrugated boxes, and paper bags, or sealing lids); and
(iii) applying plastic or paper labels, as well as in the manufacture of adhesive tapes.

The selection of an appropriate adhesive for a given substrate depends on several factors, including surface tension, solubility parameters, and viscosity [109].

Barrier adhesives applied to BOPP films act as functional layers, contributing to the reduction of gas and water vapor permeability. Among the most studied materials, polyvinyl alcohol based systems and ethylene vinyl alcohol based systems stand out, offering an oxygen barrier [110]. Polyurethane (PU) adhesives, used in BOPP lamination, can present a moderate barrier, which can be significantly improved by incorporating nanometric lamellar fillers [111]. Acrylic adhesives offer good transparency and ease of processing, with barrier properties

superior to those of PP [112]. Additionally, organic-inorganic hybrid systems, such as those obtained by sol-gel routes, have been investigated as ultrathin barrier adhesives and coatings for BOPP, showing significant barrier improvements and potential to replace metallized structures in applications focused on recyclability [113]. In general, the performance of barrier adhesives in BOPP depends on factors such as surface treatment, chemical compatibility, mechanical stability, and moisture resistance.

3.3.5. Synthetic polymer-based coatings

As seen previously, BOPP films are widely used in the packaging industry due to their good mechanical properties, transparency, and low cost. However, because they have limitations in gas- and water-vapor barrier properties, this has led to the development and use of functional polymer coatings to address these weaknesses [27,114]. Among the various synthetic coatings applied to polymers, polyvinyl alcohol (PVOH) and ethylene vinyl alcohol copolymer (EVOH) are the most frequently used in BOPP films.

Polyvinyl alcohol (PVOH) is a synthetic polymer derived from vinyl acetate, available in partially or fully hydrolyzed forms. It is colorless, odorless, and water-soluble due to its hydroxyl groups, which enable hydrogen bonding. These features provide biocompatibility and biodegradability, making PVOH attractive for sustainable food packaging [115,116]. PVOH-based films exhibit low gas permeability and excellent barrier properties, helping extend food shelf life [117]. However, their oxygen-barrier performance is affected by humidity, which limits their use [116]. Due to this sensitivity and processing challenges, PVOH is mainly applied as a coating on films such as BOPP or PET, especially for dry foods [4]. In addition to improving gas barrier properties, PVOH enhances physicochemical and functional characteristics. It offers advantages such as cost-effectiveness, low weight, good mechanical strength, sealing ability, and environmental sustainability. To further improve performance, PVOH can be combined with natural polymers like starch, cellulose, gelatin, and chitosan. Other key properties for packaging applications include wettability, transparency, solubility, mechanical strength, and thermal stability [118].

Ethylene vinyl alcohol copolymer (EVOH) is a semi-crystalline material recognized for its superior gas barrier properties, particularly against oxygen, which result from strong intermolecular interactions facilitated by hydroxyl groups. It also provides effective barriers against carbon dioxide, aromas, and volatile organic compounds, supporting its widespread use in food packaging. The barrier and processing properties of EVOH are determined by its composition, where a higher vinyl alcohol content improves barrier performance, while a higher ethylene content improves processability and decreases moisture sensitivity [119]. However, EVOH is highly sensitive to water, reducing its barrier efficiency in humid environments. Consequently, it is typically incorporated into multilayer structures and protected by hydrophobic polymers [119,120]. For BOPP, EVOH may be applied as a coating layer or coextruded to substantially enhance oxygen barrier properties, thereby enabling its use in higher-value-added packaging applications [120,121].

3.3.6. Nanomaterials applied in coating

The incorporation of nanomaterials into polymer films has emerged as a promising strategy for the development of high-performance packaging, driven by the growing demand for materials with superior barrier properties, greater thermal stability, and advanced functionality. Nanocomposites exhibit significant improvements in mechanical and barrier properties, including barrier properties against gases (such as O_2, CO_2, volatiles, and aroma compounds) and UV radiation, when compared to unmodified materials. Nanofillers commonly employed in these systems include nanoclays, carbon nanotubes, cellulose nanofibers or nanowhiskers, starch nanocrystals, and chitosan nanoparticles [122].

The use of nanomaterials in nanocoatings or nanocomposites has shown promising results in expanding the applicability of the material in high-demand packaging, without compromising its processability and maintaining potential compatibility with recycling routes. Recent studies demonstrate significant reductions in permeability and advances in environmental stability, highlighting the central role of these technologies in the new generation of functional and sustainable packaging [122–124].

3.3.7. Sustainable alternative BOPP coating systems

Currently, the plastic packaging sector is one of the most important, and global plastic production is around 400 million tons [125,126]. Plastic materials are extensively known for their highly mechanical performance, gas and water barrier properties, transparency, and cost-effectiveness [126–129]. Nevertheless, most plastic packaging materials originate from fossil fuel derivatives and are designed for single-use applications, exemplifying a linear economic model. This approach results in substantial post-consumer waste generation, contributing to environmental issues due to their recycling and degradation characteristics [126,127,130–132]. Consequently, the growing demand for sustainable solutions and a circular economy has driven increased research into alternative materials [130,131].

The shelf life of several products is limited and influenced by their intrinsic characteristics, properties, and storage conditions. Environmental factors such as light exposure, oxygen levels, temperature, and humidity can promote the degradation of the product, decreasing its durability. However, selecting appropriate packaging materials can significantly enhance preservation and extend product shelf life [133–135]. Effective packaging materials are crucial for safeguarding product quality, preventing deterioration, and maintaining visual appeal throughout the entire supply chain, from distribution and retail display to ultimate consumption [126,127,136–138]. It fulfills essential functions, such as safeguarding against contamination, spoilage, and external environmental factors [139–141]. Several packaging materials are commercialized. However, recent trends reveal a pronounced shift toward developing sustainable and multifunctional packaging alternatives, driven by both industry innovation and consumer preference [127,142–144].

BOPP is among the most extensively utilized flexible packaging materials [141]. This polymer film exhibits exceptional mechanical properties, including high tensile strength and dimensional stability due to its highly oriented molecular structure achieved through biaxial stretching, excellent charge–discharge efficiency, colorless, non-toxic, chemical resistance, good barrier, low price, and transparency [141,145–147]. However, due to its chemical inertness, wrinkling, edge defects, static electricity buildup, difficulties with printing and lamination processes, and hydrophobicity, achieving high-quality standards becomes difficult [141,148,149].

Advancing BOPP properties are vital to ensure sustainability and meet stringent environmental requirements [150], provided that the coatings are, in fact, recyclable and recycled. The development of functional coating materials has become a surface modification strategy for polymeric films [141,151,152]. This technique minimizes substrate alteration while allowing the surface functionalization [153]. Organic and inorganic materials applied in the development of coatings promote the enhancement of flexibility, processability, thermal resilience, corrosion resistance, electrical, and optical properties of several materials, such as polymers [141,154].

Fig. 4 displays BOPP film and packaging, highlighting various alternative BOPP coating systems along with their major advantages and disadvantages. Meanwhile, Table 4 presents key information regarding these alternative BOPP coating systems, summarizing their characteristics and performance metrics.

4. Regulatory aspects related to coated BOPP films

Plastics and their coatings intended for contact with food are regulated by legal frameworks that adopt positive lists of substances,

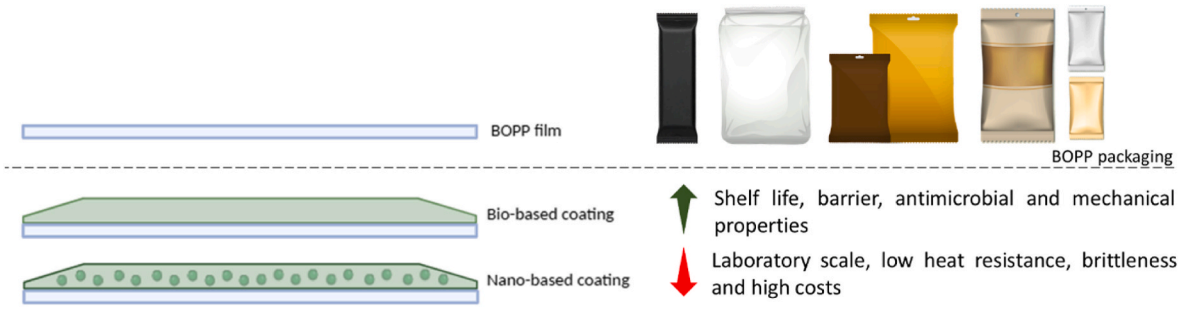


Fig. 4. BOPP film and packaging, alternative BOPP coating systems with major advantages and disadvantages (Font: author).

Table 4
Major information about alternative BOPP coating systems.

Alternative coatings	Sources	Application	Advantages	Limitations	References
Cellulose and Carboxymethyl cellulose (CMC)-based	Water-soluble cellulose polysaccharide (carboxyl groups -COOH) derivative	Oxygen and oil barrier properties; antimicrobial and mechanical properties; and thermal stability	Renewable sources, biodegradability, film-forming, mechanical strength, and high transparency	Low humidity resistance and water-binding characteristics	[139, 155–158]
Biopolymers (PLA, PHA)	**Polylactic acid (PLA):** thermoplastic matrix material derived from natural sources (corn and sugarcane). **Polyhydroxyalkanoates (PHAs):** polyesters synthesized by a range of bacteria (*Azotobacter* sp., *Pseudomonas* sp., *Bacillus* sp., and *Methylobacterium* sp.)	Compostability and increase humidity resistance	Renewable source, biocompatibility, biodegradability, transparency, moderate hydrophobicity, and adhesion properties	Poor water and gas barrier, low heat resistance, brittleness, high costs, and downstream processing	[159–163]
Polysaccharides and carbohydrates	**Animal:** chitin/chitosan; **Plant:** starch, sodium alginate, furcellaran, carrageenan, cellulose, pectin and agar; **Microbiological:** xanthan gum, pullan, guar gum and acacia gum	Shelf life; gas, aromas and lipids barrier; antimicrobial. stabilizing, and emulsifying properties	Wide availability, low cost, non-toxic, biocompatibility, biodegradability, and good film-forming properties	Hydrophilic nature, low antioxidant, antimicrobial, and light-barrier properties	[139, 164–169]
Protein	**Animal:** casein (sodium or calcium caseinate), and whey **Plant:** zein, soy bean, starch, gluten, pea, rice, wheat, lentils, quinoa, sunflower, nuts and others	Edible films with high oxygen and oil barrier, high mechanical, resistance and transparency, and smooth and stretchable properties	Solubility, film formability, cohesive/adhesive properties, density, transparency, ability, softness, flavorlessness, smoothness, biodegradability, antimicrobial and antioxidant properties	Low acceptability, higher carbon footprints and costs, hydrophilic nature, lack of functionalities such as antimicrobial and antioxidant properties, and poor mechanical properties	[164,165, 168, 170–172]
Lipids (fatty acids: FA), essential oils (EO), and wax emulsions	**FA:** caprylic, lauric, palmitic and stearic; **EO:** plant-based (fruits, seeds, and leaves) **Wax:** animal-based: beewax, wool, and shellac; plant-based: candelilla, soy, rice bran, and carnauba	Barrier, mechanical, antibacterial, and antioxidant properties	Sustainability, Biodegradability, water resistance, thermal stability, low surface energy, and mechanical qualities	Hydrophobicity, low solubility and stability, poor adhesion on the surface substrate, and bioavailability	[143, 172–180]
Nanotechnology (nanomaterials and anocomposites)	**Nanoparticles:** Inorganic nanoparticles - ZnO, Ag, SiO_2, and TiO_2; **Nanocomposites:** PLA + cellulose nanocrystals (CNC); chitosan + nano-clay; cellulose nanofiber (CNF) + chitosan; CNF + PLA	Shelf life; oxygen barrier; mechanical and antimicrobial properties; surface adhesion and printability	Sustainability, eco-friendly, hydrophobicity, transportation, quality, less toxic, cost-efficient, and consumer convenience	Nanotechnology in food formulation is on a laboratory scale, and bioaccumulation	[8,9,139, 157,181]

migration limits, and declaration of conformity requirements [182]. Increases in use of bioactive compounds, such as antioxidants and antimicrobial agents, along with the incorporation of nanomaterials with enhanced mechanical and barrier properties, offers not only significant benefits to food safety but also opportunities for the development of materials more aligned with sustainability demands. However, despite their potential, the implementation of these approaches depends on critical factors such as regulatory approval, consumer acceptance, and large-scale industrial viability. Regulatory bodies, such as the Food and Drug Administration (FDA) in the United States and the European Food Safety Authority (EFSA) in Europe, play a central role in evaluating the safety and efficacy of these materials intended for food contact. Compliance with applicable standards, labeling requirements, and good manufacturing practices (GMP) remains essential to ensure consumer confidence and promote the market entry of these materials [183–185].

Nanofillers may migrate from food packaging into food products because their decreased size and increased surface area per unit volume result in shorter diffusion distances, and higher concentration gradients. This raises concerns about consumer health and safety [122]. Numerous studies have indicated the possibility of nanomaterial migration from the polymer matrix; however, experimental evidence shows that the amounts migrated are quite small when compared to other types of migration [185].

Advances in safety assessment of nanocellulose used in food packaging show that nanocelluloses, such as cellulose nanocrystalline (CNC) and cellulose nanofibrils (CNF), offer excellent mechanical and barrier properties, as well as being biodegradable, making them promising alternatives to conventional polymers. Although derived from natural sources, their nano form requires specific toxicological studies. Recent research indicates low cytotoxicity, absence of genotoxicity, and minimal levels of migration into food. However, factors such as size, shape, and surface functionalization influence their safety. The article

highlights the lack of specific regulatory guidelines and emphasizes the need for standardized methods and further studies to ensure the safe use of nanocellulose in contact with food [186].

According to Olawore et al. [187], the risk assessment of nanomaterials used as coatings in food packaging heavily depends on regulatory frameworks conducted by agencies such as the FDA, which requires complete characterization of nanomaterials, including composition, size, state of aggregation, and migration behavior into food. According to the authors, the FDA adopts a case-by-case approach, evaluating whether the use of nanomaterials significantly alters properties that could impact human health. This includes toxicological studies, exposure data, and stability analyses of the coatings during actual packaging use. The article also highlights that, despite technological advancements, methodological gaps remain in standardized measurement of the migration and biological effects of nanomaterials, making the regulatory process more rigorous and sometimes time-consuming.

5. Recycling aspects related to coated BOPP films

Environmental considerations associated with the production of packaging materials have historically received comparatively less emphasis than the optimization of functional and performance attributes. Nevertheless, increasing regulatory pressure and heightened societal awareness have drawn attention to the environmental liabilities of certain conventional materials. Chlorine-based polymers, such as polyvinylidene chloride (PVdC) and polyvinyl chloride (PVC), as well as aluminum-based multilayer structures, have been progressively characterized as environmentally burdensome due to challenges related to their end-of-life management, recyclability, and emission profiles [182]. This shift in perception has prompted several markets worldwide to pursue the gradual replacement of these materials in packaging applications. As a result, significant research and industrial efforts have been directed toward the development of alternative barrier solutions, including tailored coating systems designed to meet the stringent requirements of chilled-food applications, while offering improved environmental compatibility [117,188,189].

The recycling of BOPP films, especially those incorporating coatings, barrier layers, or metallization, represents a critical node for the circular economy of flexible plastics. The main challenges lie in the structural complexity of these materials: frequently used in multilayer and multimaterial structures, they require expensive and complex separation processes [27,117]. The presence of barrier coatings, printing inks, and adhesives acts as a contaminant in mechanical recycling, degrading the quality of the recycled polymer (PCR), which often acquires a grayish color, and impairing its mechanical and processing properties. Furthermore, the lightness of BOPP and the high cost of recycling processes compared to the value of the final material hinder the economic viability of the cycle.

However, the industry is responding with promising solutions: compatibilization, through the addition of additives during extrusion, improves the mechanical properties and flowability of multilayer waste, allowing for its valorization. Other approaches include the development of deinking and chemical separation technologies to efficiently remove paints and coatings, as well as the exploration of chemical recycling (pyrolysis) to convert waste into valuable chemicals. In the future, "design for recycling" will gain prominence, encouraging the creation of films with molecular architecture that favors recycling, such as single-layer BOPP/BOPP structures, significantly simplifying post-consumer processing [189–191].

6. Challenges and prospects

The development of barrier coatings for BOPP films has progressed significantly, however, several technical, economic, and regulatory challenges continue to hinder their widespread industrial adoption. A primary limitation arises from the intrinsically low surface energy of BOPP, which restricts the adhesion of hydrophilic and hybrid coatings. This issue affects both solution-based approaches, such as sol–gel and layer-by-layer assembly, and vapor-phase techniques, including CVD, PECVD, and ALD. Consequently, surface activation treatments, such as corona or plasma, are often required, increasing process complexity and cost [81,175,176]. Moreover, maintaining coating adhesion under industrial conditions, including lamination, printing, and high draw ratios, remains a critical challenge, particularly for ultrathin and nanostructured coatings.

Barrier stability under real-use conditions also represents a major concern. Exposure to high humidity, temperature fluctuations, mechanical abrasion, and cyclic deformation can significantly degrade coating integrity and increase gas permeability. In vapor-deposited coatings, particularly those produced by PVD and PECVD, the presence of microstructural defects such as pinholes and microcracks can act as preferential pathways for gas diffusion. Similarly, nanostructured systems based on layered fillers, such as nanoclays or graphene, may experience reorientation or structural disruption under mechanical or environmental stress. As a result, the barrier performance achieved under laboratory conditions is not always maintained in practical applications. In addition, maintaining optical properties such as transparency and gloss remains essential for packaging applications, imposing further constraints on coating design [177,178].

From a sustainability perspective, increasing regulatory pressure toward recyclable monomaterial packaging, particularly under frameworks such as the Packaging and Packaging Waste Regulation (PPWR), requires coating technologies that deliver high barrier performance without compromising recyclability [81,179]. This necessitates the development of coatings that are compatible with existing recycling streams or can be removed during reprocessing. However, many high-performance systems, including multilayer structures and organic–inorganic hybrids, still present significant challenges in terms of recyclability and alignment with circular economy principles. Furthermore, compliance with food contact regulations, including migration limits and safety assessments, must be considered in the design of coating systems.

Looking forward, several technological approaches are emerging as promising alternatives to conventional metallization processes. Advanced vapor-phase techniques, such as low-temperature CVD, PECVD, and especially ALD, enable the formation of highly uniform, conformal, and dense coatings with reduced defect density, even on flexible substrates [75]. In parallel, bioinspired coatings with lamellar architectures have demonstrated the potential to create tortuous diffusion pathways, significantly improving gas barrier performance.

Hybrid organic–inorganic coatings are expected to advance further through improved interfacial engineering and nanoparticle dispersion strategies. Additionally, the integration of computational modeling and advanced characterization techniques, such as atom probe tomography and interface-sensitive spectroscopies, is enabling a deeper understanding of structure–property relationships governing adhesion, permeability, and failure mechanisms [177].

Ultimately, the future of barrier coatings for BOPP films will depend on achieving an optimal balance between barrier performance, recyclability, regulatory compliance, and industrial scalability. The transition from conventional metallized systems toward advanced, defect-controlled, and sustainable coating technologies is likely to define the next generation of high-performance packaging materials.

7. Conclusion

Advances in the application of barrier coatings for BOPP films demonstrate significant progress toward the development of high-performance flexible packaging capable of meeting current demands for safety, functionality, and sustainability. The literature shows that a wide variety of technologies, including hydrophilic polymer coatings,

organic-inorganic hybrid systems, nanocomposites, plasma deposition, and metallization, have been employed to overcome the intrinsic limitations of BOPP, especially its low gas barrier. These advances, however, depend heavily on the surface preparation of the substrate, since the low surface energy of BOPP requires treatments such as corona, plasma, or primers to promote adequate adhesion and stability of the coating layer, directly influencing the final performance and cost of the process.

In parallel with the technical challenges, regulatory and circularity aspects exert increasing pressure on the selection of materials and processing routes, focusing on compounds that are safe for food contact, structures compatible with mechanical recycling, and alternatives that reduce the use of metallized or halogenated layers. In this scenario, the transition to more sustainable coatings, such as biopolymers, water-soluble systems, or hybrids with less environmental impact, emerges as a consolidated trend, but still dependent on advances in performance under high humidity, mechanical stability, and economic viability.

Prospects indicate that the integration of nanomaterials, and advanced characterization techniques will enable a deeper understanding of barrier and failure mechanisms, allowing for the rational design of more efficient and recyclable structures. To enable large-scale industrial adoption, the development of coating technologies compatible with high-speed production lines will be essential, as well as regulatory harmonization and the strengthening of recycling chains. Thus, joint efforts between academic research, industry, and regulatory agencies will be fundamental to driving the development of innovative solutions that reconcile performance, safety, and sustainability for coated BOPP films.

Funding sources

This study was partly funded by the Coordination for the Improvement of Higher Education Personnel – Brazil (CAPES) – Financial Code 001. Additionally, this study received partial financial support from the National Council for Scientific and Technological Development (CNPq), grant number 301184/2025-9. This study was financed, in part, by the Grant #2024/07555-2, #2025/04105-9 and #2021/11967-6, São Paulo Research Foundation (FAPESP), Brazil, as part of the activities of the Center of Science for the Development of Solutions for the Post-Consumer Waste: Packaging and Products - CCD Circula, which also has the financial support of the following companies: Braskem, Grupo Boticário, Natura, Sonoco and Tetra Pak.

CRediT authorship contribution statement

Paula Fernanda Janetti Bócoli: Formal analysis, Investigation, Writing – original draft. **Talita Braga Brito Nogueira:** Formal analysis, Investigation, Writing – original draft. **Amanda Alves Domingos Maia:** Formal analysis, Investigation, Writing – original draft. **Luís Marangoni Júnior:** Conceptualization, Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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.

Data availability

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

References

[1] Alaburdaitė R, Krylova V. Polypropylene film surface modification for improving its hydrophilicity for innovative applications. Polym Degrad Stabil 2023;211:110334. https://doi.org/10.1016/j.polymdegradstab.2023.110334.
[2] Adam HB, Yousfi M, Maazouz A, Lamnawar K. Recycling of multilayer polymeric barrier films: an overview of recent pioneering works and main challenges. Macromol Mater Eng 2025;310. https://doi.org/10.1002/mame.202400414.
[3] Bauer A-S, Tacker M, Uysal-Unalan I, Cruz RMS, Varzakas T, Krauter V. Recyclability and redesign challenges in multilayer flexible food packaging—A review. Foods 2021;10:2702. https://doi.org/10.3390/foods10112702.
[4] Lemos A, Soares B, Moreira C, Sarantopoulos C, Borges D, Ito D, Garcia E, Teixeira F, Queiroz G, Pitta J, Oliveira L, Coltro L, Padula M, Perez M, Souza R, Alves R, Jaime S, Gonçalves T, Karaski T. Embalagens plásticas flexíveis: principais polímeros e avaliação de propriedades. second ed. 2017. Cetea, Campinas.
[5] Viswanathan VP, Kulandhaivelu SV, Manivasakan K, Ramakrishnan R. Development of biodegradable packaging films from carboxymethyl cellulose and oxidised natural rubber latex. Int J Biol Macromol 2024;262:129980. https://doi.org/10.1016/j.ijbiomac.2024.129980.
[6] Azizi M, Jahanbin K, Shariatifar N. Evaluation of whey protein coating containing nanoliposome dill (Anethum graveolens L.) essential oil on microbial, physicochemical and sensory changes of rainbow trout fish. Food Chem X 2024;21:101110. https://doi.org/10.1016/j.fochx.2023.101110.
[7] Ureña M, Phùng TT-T, Gerometta M, de Siqueira Oliveira L, Chanut J, Domenek S, Dole P, Roudaut G, Lagorce A, Karbowiak T. Potential of polysaccharides for food packaging applications. Part 1/2 : an experimental review of the functional properties of polysaccharide coatings. Food Hydrocoll 2023;144:108955. https://doi.org/10.1016/j.foodhyd.2023.108955.
[8] Kışla D, Gökmen GG, Akdemir Evrendilek G, Akan T, Vlčko T, Kulawik P, Režek Jambrak A, Ozogul F. Recent developments in antimicrobial surface coatings: various deposition techniques with nanosized particles, their application and environmental concerns. Trends Food Sci Technol 2023;135:144–72. https://doi.org/10.1016/j.tifs.2023.03.019.
[9] Rovera C, Ghaani M, Farris S. Nano-inspired oxygen barrier coatings for food packaging applications: an overview. Trends Food Sci Technol 2020;97:210–20. https://doi.org/10.1016/j.tifs.2020.01.024.
[10] Apicella A, Barbato A, Garofalo E, Incarnato L, Scarfato P. Effect of PVOH/PLA + wax coatings on physical and functional properties of biodegradable food packaging films. Polymers 2022;14:935. https://doi.org/10.3390/polym14050935.
[11] Idris A, Muntean A, Mesic B, Lestelius M, Javed A. Oxygen barrier performance of poly(vinyl alcohol) coating films with different induced crystallinity and model predictions. Coatings 2021;11:1253. https://doi.org/10.3390/coatings11101253.
[12] Darvish F, Mostofi Sarkari N, Khani M, Eslami E, Shokri B, Mohseni M, Ebrahimi M, Alizadeh M, Dee CF. Direct plasma treatment approach based on non-thermal gliding arc for surface modification of biaxially-oriented polypropylene with post-exposure hydrophilicity improvement and minus aging effects. Appl Surf Sci 2020;509:144815. https://doi.org/10.1016/j.apsusc.2019.144815.
[13] Šrámková P, Kelar Tučeková Z, Fleischer M, Kelar J, Kováčik D. Changes in surface characteristics of BOPP foil after treatment by ambient air plasma generated by coplanar and volume dielectric barrier discharge. Polymers 2021;13:4173. https://doi.org/10.3390/polym13234173.
[14] Song G, Tan DQ. Atomic layer deposition for polypropylene film engineering—A review. Macromol Mater Eng 2020;305. https://doi.org/10.1002/mame.202000127.
[15] Nguyen HL, Tran TH, Hao LT, Jeon H, Koo JM, Shin G, Hwang DS, Hwang SY, Park J, Oh DX. Biorenewable, transparent, and oxygen/moisture barrier nanocellulose/nanochitin-based coating on polypropylene for food packaging applications. Carbohydr Polym 2021;271. https://doi.org/10.1016/j.carbpol.2021.118421.
[16] Hossain MdT, Shahid MdA, Mahmud N, Habib A, Rana MdM, Khan SA, Hossain MdD. Research and application of polypropylene: a review. Discover Nano 2024;19:2. https://doi.org/10.1186/s11671-023-03952-z.
[17] Maddah HA. Polypropylene as a promising plastic - a review. Am J Polym Sci 2016;6:1–11. https://doi.org/10.5923/j.ajps.20160601.01.
[18] Sanetuntikul J, Ketpang K, Naknaen P, Narupai B, Petchwattana N. A circular economy use of waste metalized plastic film as a reinforcing filler in recycled polypropylene packaging for injection molding applications. Clean Eng Technol 2023;17. https://doi.org/10.1016/j.clet.2023.100683.
[19] Antosik AK, Kowalska U, Stobińska M, Dzięcioł P, Pieczykolan M, Kozłowska K, Bartkowiak A. Development and characterization of bioactive polypropylene films for food packaging applications. Polymers 2021;13. https://doi.org/10.3390/polym13203478.
[20] DeMeuse MT, editor. Biaxial stretching of film. Woodheat Publishing Limited; 2011.
[21] Market data forecast, polypropylene market. 1–175, https://www.marketdataforecast.com/market-reports/polypropylene-market. [Accessed 30 August 2025].
[22] Aniunoh K, Harrison GM. The processing of polypropylene cast films. I. Impact of material properties and processing conditions on film formation. Polym Eng Sci 2010;50:1151–60. https://doi.org/10.1002/pen.21637.
[23] Gocek I, Adanur S. Effect of processing parameters on polypropylene film properties. Int J Modern Eng Res 2012;2:3056–60.

[24] Mckeen LW, editor. Permeability properties of plastics and elastomers. fourth ed. Matthew Deans; 2017.
[25] Karger-Kocsis J, editor. Polypropylene: an A-Z reference. Dordrecht: Springer Netherlands; 1999. https://doi.org/10.1007/978-94-011-4421-6.
[26] Kanai T, Uehara H, Sakauchi K, Yamada T. Stretchability and properties of biaxially oriented polypropylene film. Int Polym Process 2006;21:449–56. https://doi.org/10.3139/217.0987.
[27] Adeniyi AG, Iwuozor KO, Emenike EC, Voskressensky LG, Luque R. Advances and challenges in production and valorization of biaxially oriented polypropylene (BOPP). Funct Compos Struct 2025;7:022001. https://doi.org/10.1088/2631-6331/add6ed.
[28] Agassant J-F, Demay Y. Investigation of the polymer coextrusion process: a review. Polymers 2022;14:1309. https://doi.org/10.3390/polym14071309.
[29] Wypych G. Handbook of polymers. second ed. ChemTec Publishing; 2016.
[30] Song Y, Tzeng P, Grunlan JC. Super oxygen and improved water vapor barrier of polypropylene film with polyelectrolyte multilayer nanocoatings. Macromol Rapid Commun 2016;37:963–8. https://doi.org/10.1002/marc.201600140.
[31] Jang J, Lee DK. Oxygen barrier properties of biaxially oriented polypropylene/polyvinyl alcohol blend films. Polymer 2004;45:1599–607. https://doi.org/10.1016/j.polymer.2003.12.046.
[32] Zabihzadeh Khajavi M, Ebrahimi A, Yousefi M, Ahmadi S, Farhoodi M, Mirza Alizadeh A, Taslikh M. Strategies for producing improved oxygen barrier materials appropriate for the food packaging sector. Food Eng Rev 2020;12:346–63. https://doi.org/10.1007/s12393-020-09235-y.
[33] Fukuzumi H, Saito T, Isogai A. Influence of TEMPO-oxidized cellulose nanofibril length on film properties. Carbohydr Polym 2013;93:172–7. https://doi.org/10.1016/j.carbpol.2012.04.069.
[34] Coltro L, V Alves RM. Tratamento superficial de filmes flexíveis por plasma. Inform CETEA 2001;13:1–5.
[35] Sun Y, Liu Z, Zhao T, Wang Y, Liu J, Chen J, Hu Q, Li Z-M, Yang G, Zhong G-J. Investigation of surface changes of biaxially oriented polypropylene films by multiple organic/inorganic nanocomposite coatings for enhanced water-based ink printing. Surf Interfaces 2025;64:106364. https://doi.org/10.1016/j.surfin.2025.106364.
[36] Glaser TK, Plohl O, Vesel A, Ajdnik U, Ulrih NP, Hrnčič MK, Bren U, Zemljič LF. Functionalization of polyethylene (PE) and polypropylene (PP) material using chitosan nanoparticles with incorporated resveratrol as potential active packaging. Materials 2019;12. https://doi.org/10.3390/ma12132118.
[37] Honarvar Z, Farhoodi M, Khani MR, Mohammadi A, Shokri B, Ferdowsi R, Shojaee-Aliabadi S. Application of cold plasma to develop carboxymethyl cellulose-coated polypropylene films containing essential oil. Carbohydr Polym 2017;176:1–10. https://doi.org/10.1016/j.carbpol.2017.08.054.
[38] Janík R, Ďurišová S, Kohutiar M, Escherová J, Moricová K. Surface characteristics of thermoplastic films indirectly modified by plasma under static conditions. Mater Werkst 2025;56:743–56. https://doi.org/10.1002/mawe.202400365.
[39] Kohutiar M, Krbata M, Janik R, Fekiac JJ, Kakosova L, Escherova J. Effect of DCSBD plasma treatment on the mechanical properties of polymer films. Manuf Technol J 2025;25:37–44. https://doi.org/10.21062/mft.2025.012.
[40] Prorokova NP, Kumeeva TY, Vavilova SY, V Kholodkov I, Kuznetsov OY, Bouznik VM. Imparting antimicrobial properties to polypropylene non-woven material using plasma fluorination. Russ Chem Bull 2025;74:834–45. https://doi.org/10.1007/s11172-025-4577-7.
[41] Chen X, Rossi D, Guo Y, Wan QG, Chen X, Mohler CE, Kuo TC, Chen Z. Effect of Corona treatment on the adhesion between a two-component polyurethane adhesive and polypropylene. Macromolecules 2024;57:6646–56. https://doi.org/10.1021/acs.macromol.4c00897.
[42] Usha ZR, Babiker DMD, Yu R, Yang J, Chen W, Chen X, Li L. Super hydrophilic modified biaxially oriented polypropylene microporous membrane for excellent gravity-driven oil/water emulsion separation. J Membr Sci 2022;660:120840. https://doi.org/10.1016/j.memsci.2022.120840.
[43] Ding LP, Zhang XY, Wang YQ. Study on the behavior of BOPP film treated by Corona discharge. Coatings 2020;10. https://doi.org/10.3390/coatings10121195.
[44] Kalapat N, Arnornsakchai T. Surface modification of biaxially oriented polypropylene (BOPP) film using acrylic acid-corona treatment: part I. Properties and characterization of treated films. Surf Coat Technol 2012;207:594–601. https://doi.org/10.1016/j.surfcoat.2012.07.081.
[45] Kalapat N, Amornsakchai T, Srikhirin T. Surface modification of biaxially oriented polypropylene (BOPP) film using acrylic acid-corona treatment: part II. Long term aging surface properties. Surf Coat Technol 2013;234:67–75. https://doi.org/10.1016/j.surfcoat.2013.05.012.
[46] Franco P, Incarnato L, De Marco I. Supercritical CO2 impregnation of α-tocopherol into PET/PP films for active packaging applications. J CO2 Util 2019;34:266–73. https://doi.org/10.1016/j.jcou.2019.06.012.
[47] Cozzolino CA, Pozzoli S, La Vecchia S, Piergiovanni L, Farris S. An alternative approach to control the oxygen permeation across single-dose coffee capsules. Food Packag Shelf Life 2015;4:19–25. https://doi.org/10.1016/j.fpsl.2015.03.001.
[48] Strobel M, Strobel JM, Jones V, Lechuga H, Lyons CS. Effect on wettability of the topography and oxidation state of biaxially oriented poly(propylene) film. J Adhes Sci Technol 2019;33:1644–57. https://doi.org/10.1080/01694243.2019.1604304.
[49] Liu S, Shi R, Yang Y, Li L, Wang G. Effect of supercritical carbon dioxide treatment on physical properties of polypropylene films. J Appl Polym Sci 2025;142:e56566. https://doi.org/10.1002/app.56566.
[50] Šćetar M, Kurek M, Režek Jambrak A, Debeaufort F, Galić K. Effect of high power ultrasound on physical–chemical properties of polypropylene films aimed for food packaging: structure and surface features. Polym Bull 2019;76:1007–21. https://doi.org/10.1007/s00289-018-2416-9.
[51] Vukušić T, Vesel A, Holc M, Šćetar M, Jambrak AR, Mozetič M. Modification of physico-chemical properties of acryl-coated polypropylene foils for food packaging by reactive particles from oxygen plasma. Materials 2018;11. https://doi.org/10.3390/ma11030372.
[52] Mostafavi AH, Mishra AK, Gallucci F, Kim JH, Ulbricht M, Coclite AM, Hosseini SS. Advances in surface modification and functionalization for tailoring the characteristics of thin films and membranes via chemical vapor deposition techniques. J Appl Polym Sci 2023;140:e53720. https://doi.org/10.1002/app.53720.
[53] Bahrami R, Zibaei R, Hashami Z, Hasanvand S, Garavand F, Rouhi M, Jafari SM, Mohammadi R. Modification and improvement of biodegradable packaging films by cold plasma; a critical review. Crit Rev Food Sci Nutr 2022;62:1936–50. https://doi.org/10.1080/10408398.2020.1848790.
[54] Louzi VC, Campos JS de C. Corona treatment applied to synthetic polymeric monofilaments (PP, PET, and PA-6). Surf Interfaces 2019;14:98–107. https://doi.org/10.1016/j.surfin.2018.12.005.
[55] Liu Z, Chen L, Zhao T, Wang J, Mao H, Yang G, Lv H, Zhu M, Zhong G. Preparation of BOPP/SiO_2@TiO_2 nanocomposite film and its waterborne ink printing performance study. N Chem Mater 2025;53:123–8. https://doi.org/10.19817/j.cnki.issn1006-3536.2025.06.003.
[56] Strobel M, Jones V, Lyons CS, Ulsh M, Kushner MJ, Dorai R, Branch MC. A comparison of corona-treated and flame-treated polypropylene films. Plasma Polym 2003;8:61–95. https://doi.org/10.1023/A:1022817909276.
[57] Farris S, Pozzoli S, Biagioni P, Duó L, Mancinelli S, Piergiovanni L. The fundamentals of flame treatment for the surface activation of polyolefin polymers – a review. Polymer 2010;51:3591–605. https://doi.org/10.1016/j.polymer.2010.05.036.
[58] Williams DF, Abel M-L, Grant E, Hrachova J, Watts JF. Flame treatment of polypropylene: a study by electron and ion spectroscopies. Int J Adhesion Adhes 2015;63:26–33. https://doi.org/10.1016/j.ijadhadh.2015.07.009.
[59] Pijpers AP, Meier RJ. Adhesion behaviour of polypropylenes after flame treatment determined by XPS(ESCA) spectral analysis. J Electron Spectrosc Relat Phenom 2001;121:299–313. https://doi.org/10.1016/S0368-2048(01)00341-3.
[60] Sutherland I, Brewis DM, Health RJ, Sheng E. Modification of polypropylene surfaces by flame treatment. Surf Interface Anal 1991;17:507–10. https://doi.org/10.1002/sia.740170717.
[61] Nemani SK, Annavarapu RK, Mohammadian B, Raiyan A, Heil J, Haque MA, Abdelaal A, Sojoudi H. Surface modification of polymers: methods and applications. Adv Mater Interfac 2018;5:1801247. https://doi.org/10.1002/admi.201801247.
[62] Okolie JA, Nanda S, Dalai AK, Kozinski JA. Chapter 9 - advances in the industrial applications of supercritical carbon dioxide. In: Nanda S, Vo D-VN, Nguyen V-H, editors. Carbon dioxide capture and conversion. Elsevier; 2022. p. 237–56. https://doi.org/10.1016/B978-0-323-85585-3.00008-0.
[63] Wang J, Guo H, Zeng S, Du J, Zhang Q, Wang K. Thin, largescale processed, high-temperature resistant capacitor films based on polypropylene/cycloolefin copolymer blend. Chem Eng J 2024;492:152237. https://doi.org/10.1016/j.cej.2024.152237.
[64] Wu Q, Ding M, Guo J, Nie M, Wang Q, Wu L. Layer-by-layer stacking, low-temperature welding strategy to effectively recycle biaxially-oriented polypropylene film waste. Polymer (Guildf) 2022;253:125006. https://doi.org/10.1016/j.polymer.2022.125006.
[65] Marangoni Júnior L, Augusto PED, Vieira RP, Borges DF, Ito D, Teixeira FG, Dantas FBH, Padula M. Food-package-processing relationships in emerging technologies: ultrasound effects on polyamide multilayer packaging in contact with different food simulants. Food Res Int 2023;163:112217. https://doi.org/10.1016/j.foodres.2022.112217.
[66] Marangoni Júnior L, Augusto PED, Perez MÂF, Soares BMC, Kiyataka PHM, Dantas FBH, Padula M. Food-packaging interaction during ultrasound processing: migration of monomers from multilayer polyamide packages to different food simulants. J Food Meas Char 2024;18:1452–62. https://doi.org/10.1007/s11694-023-02259-y.
[67] Marangoni Júnior L, Augusto PED, Soares BMC, Vieira RP, Moraes GH, Kiyataka PHM, Dantas FBH, Padula M. Effect of ultrasonic processing on the physical-chemical properties and migration of metallized flexible packaging materials. J Food Meas Char 2025;19:7314–28. https://doi.org/10.1007/s11694-025-03475-4.
[68] de Almeida MM, Castanha N, Bócoli PFJ, Kiyataka PHM, Soares BMC, Augusto PED, Dantas FBH, Júnior LM. Exploring the effects of ultrasound processing on food packaging laminated with aluminum foil. Polym Eng Sci 2025. https://doi.org/10.1002/pen.70193.
[69] Scetar M, Kurek M, Jambrak AR, Debeaufort F, Galic K. Influence of high power ultrasound on physical - chemical properties of polypropylene films aimed for food packaging: barrier and contact angle features. Polym Int 2017;66:1572–8. https://doi.org/10.1002/pi.5415.
[70] Du H, Kobayashi M, Ono R. Synergistic effects between oxygen radicals and ozone on polymer surface functionalization: quantitative analysis and mechanistic insights. Appl Surf Sci 2025;711:164090. https://doi.org/10.1016/j.apsusc.2025.164090.
[71] Wanke CH, Barbosa LG, Hübner JVM, Horowitz F, Mauler RS, de Oliveira RVB. Recuperação hidrofóbica de polipropileno tratado por VUV ou plasma. Polímeros 2012;22.

[72] Nie H-Y, Walzak MJ, Berno B, McIntyre NS. Atomic force microscopy study of polypropylene surfaces treated by UV and ozone exposure: modification of morphology and adhesion force. Appl Surf Sci 1999;144–145:627–32. https://doi.org/10.1016/S0169-4332(98)00879-4.
[73] d'Eon J, Zhang W, Chen L, Berry RM, Zhao B. Coating cellulose nanocrystals on polypropylene and its film adhesion and mechanical properties. Cellulose 2017; 24:1877–88. https://doi.org/10.1007/s10570-017-1222-0.
[74] Grimm OC, Welsh EA, Pang R, Whitten JE. Comparison of oxidative treatments of polypropylene films and fibers to promote zinc oxide nanoparticle adhesion. J Adhes Sci Technol 2022;36:302–16. https://doi.org/10.1080/01694243.2021.1918917.
[75] Dufour T. From basics to frontiers: a comprehensive review of plasma-modified and plasma-synthesized polymer films. Polymers 2023;15:3607. https://doi.org/10.3390/polym15173607.
[76] Merche D, Vandencasteele N, Reniers F. Atmospheric plasmas for thin film deposition: a critical review. Thin Solid Films 2012;520:4219–36. https://doi.org/10.1016/j.tsf.2012.01.026.
[77] Bertin M, Leitao EM, Bickerton S, Verbeek CJR. A review of polymer surface modification by cold plasmas toward bulk functionalization. Plasma Process Polym 2024;21:2300208. https://doi.org/10.1002/ppap.202300208.
[78] Mozetič M. Low-pressure non-equilibrium plasma technologies: scientific background and technological challenges. Rev Mod Plasma Phys 2025;9:25. https://doi.org/10.1007/s41614-025-00201-x.
[79] Sellin N, Campos JS de C. Surface composition analysis of PP films treated by corona discharge. Mater Res 2003;6.
[80] Strobel M, C BM, Michael U, S KR, Seth K, Lyons CS. Flame surface modification of polypropylene film. J Adhes Sci Technol 1996;10:515–39. https://doi.org/10.1163/156856196X00562.
[81] Cabrini A, Ghalayani Esfahani A, Petraconi A, Lavorgna M, De Nardo L, Buonocore GG, Andrade RJE, Cerruti P. Ultrasonic spray deposition of PEGDE-crosslinked chitosan/graphene oxide coatings for enhancing gas barrier properties of polybutylene succinate films. Prog Org Coating 2023;183:107760. https://doi.org/10.1016/j.porgcoat.2023.107760.
[82] Lindner M, Schmid M. Thickness measurement methods for physical vapor deposited aluminum coatings in packaging applications: a review. Coatings 2017; 7:9. https://doi.org/10.3390/coatings7010009.
[83] Pierson HO. Handbook of chemical vapor deposition (CVD). second ed. 2021. Norwich.
[84] Ohring M. Materials science of thin films. Elsevier; 2002. https://doi.org/10.1016/B978-0-12-524975-1.X5000-9.
[85] Milella A, Palumbo F. Plasma-enhanced chemical vapor deposition. In: Encyclopedia of membranes. Berlin Heidelberg, Berlin, Heidelberg: Springer; 2014. p. 1–3. https://doi.org/10.1007/978-3-642-40872-4_1106-1.
[86] George SM. Atomic layer deposition: an overview. Chem Rev 2010;110:111–31. https://doi.org/10.1021/cr900056b.
[87] Mattox DM. Physical vapor deposition (PVD) processes. Met Finish 2001;99: 409–23. https://doi.org/10.1016/S0026-0576(01)85301-0.
[88] Martin PM. Handbook of deposition technologies for films and coatings: science, applications and technolog. third ed. William Andrew; 2009.
[89] Panjan P, Drnovšek A, Gselman P, Čekada M, Panjan M. Review of growth defects in thin films prepared by PVD techniques. Coatings 2020;10:447. https://doi.org/10.3390/coatings10050447.
[90] Vu H-AT, Ngoc MN, Pham AT, Nguyen VH. Vapor-phase protective coatings for polymers: advances and challenges in ALD and VPI technologies. Polym Degrad Stabil 2024;230:111070. https://doi.org/10.1016/j.polymdegradstab.2024.111070.
[91] Snyders R, Hegemann D, Thiry D, Zabeida O, Klemberg-Sapieha J, Martinu L. Foundations of plasma enhanced chemical vapor deposition of functional coatings. Plasma Sources Sci Technol 2023;32:074001. https://doi.org/10.1088/1361-6595/acdabc.
[92] Lahtinen K, Maydannik P, Seppänen T, Cameron DC, Johansson P, Kotkamo S, Kuusipalo J. Protecting BOPP film from UV degradation with an atomic layer deposited titanium oxide surface coating. Appl Surf Sci 2013;282:506–11. https://doi.org/10.1016/j.apsusc.2013.06.002.
[93] Vähä-Nissi M, Pitkänen M, Salo E, Sievänen-Rahijärvi J, Putkonen M, Harlin A. Atomic layer deposited thin barrier films for packaging. Cellul Chem Technol 2015;49:575–85.
[94] Xie F. Biopolymer-based multilayer films and coatings for food preservation: an update of the recent development. Curr Food Sci Technol Rep 2023;1:1–12. https://doi.org/10.1007/s43555-023-00002-8.
[95] Ghisoni F, Fiorati A, De Nardo L. Design strategies for sustainable gas barrier coatings in food packaging via wet deposition technologies. Food Packag Shelf Life 2025;52:101635. https://doi.org/10.1016/j.fpsl.2025.101635.
[96] Huang H-D, Ren P-G, Zhong G-J, Olah A, Li Z-M, Baer E, Zhu L. Promising strategies and new opportunities for high barrier polymer packaging films. Prog Polym Sci 2023;144:101722. https://doi.org/10.1016/j.progpolymsci.2023.101722.
[97] Wu F, Misra M, Mohanty AK. Challenges and new opportunities on barrier performance of biodegradable polymers for sustainable packaging. Prog Polym Sci 2021;117. https://doi.org/10.1016/j.progpolymsci.2021.101395.
[98] Elsayed DM, Abdelbasir SM, Abdel-Ghafar HM, Salah BA, Sayed SA. Silver and copper nanostructured particles recovered from metalized plastic waste for antibacterial applications. J Environ Chem Eng 2020;8:103826. https://doi.org/10.1016/j.jece.2020.103826.
[99] Zhang H, Kang Z, Sang J, Hirahara H. Surface metallization of ABS plastics for nickel plating by molecules grafted method. Surf Coat Technol 2018;340:8–16. https://doi.org/10.1016/j.surfcoat.2018.02.005.
[100] Lemos AB, Sarantópoulos CIG, Ito D, Garcia EEC, Queiroz G de C, Borghetti J, Oliveira LM, Coltro L, Padula M, Alves RMV, Jaime SBM. Embalagens plásticas rígidas: principais polímeros e avaliação da qualidade. Campinas: Cetea/Ital; 2008.
[101] Rath MC. Metalized plastic: a material for a better world. Curr Sci 2024;126:671. https://doi.org/10.18520/cs/v126/i6/671-675.
[102] Bishop CA, Mount EM. Vacuum metallizing for flexible packaging. In: Multilayer flexible packaging. Elsevier; 2016. p. 235–55. https://doi.org/10.1016/B978-0-323-37100-1.00015-6.
[103] Groner MD, George SM, McLean RS, Carcia PF. Gas diffusion barriers on polymers using Al2O3 atomic layer deposition. Appl Phys Lett 2006;88. https://doi.org/10.1063/1.2168489.
[104] Leccese F, Pirondi A, Moroni F, Guadagno R, Rimediotti F, Sullo L. Mechanical characterization of innovative recyclable monomaterial films and laminates for food packaging. Proc Inst Mech Eng Part L 2025. https://doi.org/10.1177/14644207251324375.
[105] Struller C, Kelly P, Copeland N. Conversion of aluminium oxide coated films for food packaging applications—From a single layer material to a complete pouch. Food Packag Shelf Life 2019;20:100309. https://doi.org/10.1016/j.fpsl.2019.100309.
[106] Kelly PJ, Struller CF, Copeland NJ, Tobin V, Assender HE, Holliday CW, Read SJ. Aluminium oxide barrier layers and their conversion for packaging applications. 518–523, https://doi.org/10.14332/svc15.proc.1898; 2016.
[107] Mittal KL, Mittal KL. Metallized plastics 2. Boston, MA: Springer US; 1991. https://doi.org/10.1007/978-1-4899-0735-6.
[108] Liu Q, Xie X, Zhong Y, Fan H, Qv X. Research on waterborne printing varnish and anti-adhesion. 614–619, https://doi.org/10.1007/978-981-16-0503-1_88; 2021.
[109] Selke SEM, Culter JD. Plastics packaging: properties, processing. Applications, and regulations. third ed. Munich: Hanser Publishers; 2016.
[110] Schmiedt R, Krainz M, Tosic K, Sharbafian F, Krauter S, Krauter V, Novak M, Rainer B, Washüttl M, Apprich S. Impact of EVOH, ormocer® coating, and printed labels on the recyclability of polypropylene for packaging applications. Polymers 2025;17:3332. https://doi.org/10.3390/polym17243332.
[111] Lagaron JM, Catalá R, Gavara R. Structural characteristics defining high barrier properties in polymeric materials. Mater Sci Technol 2004;20:1–7. https://doi.org/10.1179/026708304225010442.
[112] McKeen LW. Permeability properties of plastics and elastomers. fourth ed. Elsevier; 2017. https://doi.org/10.1016/C2015-0-06836-8.
[113] Sanchez C, Julián B, Belleville P, Popall M. Applications of hybrid organic–inorganic nanocomposites. J Mater Chem 2005;15:3559. https://doi.org/10.1039/b509097k.
[114] Kausar A. Polymer coating technology for high performance applications: fundamentals and advances. J Macromol Sci, Part A 2018;55:440–8. https://doi.org/10.1080/10601325.2018.1453266.
[115] Panda PK, Sadeghi K, Seo J. Recent advances in poly (vinyl alcohol)/natural polymer based films for food packaging applications: a review. Food Packag Shelf Life 2022;33:100904. https://doi.org/10.1016/j.fpsl.2022.100904.
[116] Nyflött Å, Meriçer Ç, Minelli M, Moons E, Järnström L, Lestelius M, Baschetti MG. The influence of moisture content on the polymer structure of polyvinyl alcohol in dispersion barrier coatings and its effect on the mass transport of oxygen. J Coating Technol Res 2017;14:1345–55. https://doi.org/10.1007/s11998-017-9937-2.
[117] Sharbafian F, Tosic K, Schmiedt R, Novak M, Krainz M, Rainer B, Apprich S. Investigation and comparison of alternative oxygen barrier coatings for flexible PP films as food packaging material. Coatings 2024;14:1086. https://doi.org/10.3390/coatings14091086.
[118] Panda PK, Sadeghi K, Seo J. Recent advances in poly (vinyl alcohol)/natural polymer based films for food packaging applications: a review. Food Packag Shelf Life 2022;33:100904. https://doi.org/10.1016/j.fpsl.2022.100904.
[119] Maes C, Luyten W, Herremans G, Peeters R, Carleer R, Buntinx M. Recent updates on the barrier properties of ethylene vinyl alcohol copolymer (EVOH): a review. Polym Rev 2018;58:209–46. https://doi.org/10.1080/15583724.2017.1394323.
[120] Reiners UDr, Piasente F. Thin BOPP barrier films barriers against mineral oil, flavours & gases. J Appl Packag Res 2016;8.
[121] Mueller K, Schoenweitz C, Langowski H-C. Thin laminate films for barrier packaging application – influence of Down gauging and substrate surface properties on the permeation properties. Packag Technol Sci 2012;25:137–48. https://doi.org/10.1002/pts.966.
[122] Zhou X, Zhou X, Zhou L, Jia M, Xiong Y. Nanofillers in novel food packaging systems and their toxicity issues. Foods 2024;13:2014. https://doi.org/10.3390/foods13132014.
[123] Kim DH, Ryu YS, Kim SH. Improvements in the oxygen barrier property of polypropylene nanocomposites. Polym Adv Technol 2018;29:2655–64. https://doi.org/10.1002/pat.4379.
[124] Jung B-N, Jung H-W, Kang D-H, Kim G-H, Shim J-K. A study on the oxygen permeability behavior of nanoclay in a polypropylene/nanoclay nanocomposite by biaxial stretching. Polymers 2021;13:2760. https://doi.org/10.3390/polym13162760.
[125] Plastics Europe, Plastics- the facts 2022: an analysis of European plastics production, demand, conversion and end-of-life management. Bruxelas; 2022.
[126] Farrell R, Cortese YJ, Devine DM, Gately N, Rueda M, Rodriguez L, Pezzoli R. The function and properties of common food packaging materials and their suitability

for reusable packaging: the transition from a linear to circular economy. Curr Res Green Sustain Chem 2024;9. https://doi.org/10.1016/j.crgsc.2024.100429.
[127] Hussain S, Akhter R, Maktedar SS. Advancements in sustainable food packaging: from eco-friendly materials to innovative technologies. Sustain Food Technol 2024. https://doi.org/10.1039/d4fb00084f.
[128] Chandra R, Yadav S. Potential of Typha angustifolia for phytoremediation of heavy metals from aqueous solution of phenol and melanoidin. Ecol Eng 2010;36:1277–84. https://doi.org/10.1016/j.ecoleng.2010.06.003.
[129] Ghasemlou M, Barrow CJ, Adhikari B. The future of bioplastics in food packaging: an industrial perspective. Food Packag Shelf Life 2024;43. https://doi.org/10.1016/j.fpsl.2024.101279.
[130] (Anya) Phelan A, Meissner K, Humphrey J, Ross H. Plastic pollution and packaging: corporate commitments and actions from the food and beverage sector. J Clean Prod 2022;331. https://doi.org/10.1016/j.jclepro.2021.129827.
[131] Kinn MC. An innovative approach to closing the loop in a circular plastic economy by upcycling single-use post-consumer thin film plastic packaging waste into durable plastic products. Mater Circ Econ 2024;6:59. https://doi.org/10.1007/s42824-024-00152-7.
[132] Xue W, Zhu J, Sun P, Yang F, Wu H, Li W. Permeability of biodegradable film comprising biopolymers derived from marine origin for food packaging application: a review. Trends Food Sci Technol 2023;136:295–307. https://doi.org/10.1016/j.tifs.2023.05.001.
[133] lacovone C, Guz L, Famá L. Sustainable innovations in food packaging: Antioxidant basil-enriched cassava starch films with UV protection and enhanced water and mechanical resistance. Food Packag Shelf Life 2024;45. https://doi.org/10.1016/j.fpsl.2024.101324.
[134] Yeo JCC, Muiruri JK, Fei X, Wang T, Zhang X, Xiao Y, Thitsartarn W, Tanoto H, He C, Li Z. Innovative biomaterials for food packaging: unlocking the potential of polyhydroxyalkanoate (PHA) biopolymers. Biomater Adv 2024;163. https://doi.org/10.1016/j.bioadv.2024.213929.
[135] Das PP, Prathapan R, Ng KW. Advances in biomaterials based food packaging systems: current status and the way forward. Biomater Adv 2024;164. https://doi.org/10.1016/j.bioadv.2024.213988.
[136] Kumari S, Debbarma R, Nasrin N, Khan T, Taj S, Bhuyan T. Recent advances in packaging materials for food products. Food Bioeng 2024;3:236–49. https://doi.org/10.1002/fbe2.12096.
[137] Kalyani P, Das PP, Khandelwal M. Utilization of natural fiber–derived active agents for shelf life extension of broccoli (Brassica oleracea L.) and guava (Psidium guajava). Biomass Convers Biorefinery 2023. https://doi.org/10.1007/s13399-023-04889-0.
[138] Das A, Ringu T, Ghosh S, Pramanik N. A comprehensive review on recent advances in preparation, physicochemical characterization, and bioengineering applications of biopolymers. Polym Bull 2023;80:7247–312. https://doi.org/10.1007/s00289-022-04443-4.
[139] Rout SS, Pradhan KC. A review on antimicrobial nano-based edible packaging: sustainable applications and emerging trends in food industry. Food Control 2024;163. https://doi.org/10.1016/j.foodcont.2024.110470.
[140] Pascall MA, DeAngelo K, Richards J, Arensberg MB. Role and importance of functional food packaging in specialized products for vulnerable populations: implications for innovation and policy development for sustainability. Foods 2022;11. https://doi.org/10.3390/foods11193043.
[141] Sun Y, Liu Z, Zhao T, Wang Y, Liu J, Chen J, Hu Q, Li Z-M, Yang G, Zhong G-J. Investigation of surface change of biaxially oriented polypropylene films by multiple organic/inorganic nanocomposite coatings for enhanced water-based ink printing. https://doi.org/10.1016/j.surfin.2025.106364; 2025.
[142] Shlush E, Davidovich-Pinhas M. Bioplastics for food packaging. Trends Food Sci Technol 2022;125:66–80. https://doi.org/10.1016/j.tifs.2022.04.026.
[143] Nath PC, Sharma R, Debnath S, Sharma M, Inbaraj BS, Dikkala PK, Nayak PK, Sridhar K. Recent trends in polysaccharide-based biodegradable polymers for smart food packaging industry. Int J Biol Macromol 2023;253. https://doi.org/10.1016/j.ijbiomac.2023.127524.
[144] Hassoun A, Boukid F, Ozogul F, Aït-Kaddour A, Soriano JM, Lorenzo JM, Perestrelo R, Galanakis CM, Bono G, Bouyahya A, Bhat Z, Smaoui S, Jambrak AR, Câmara JS. Creating new opportunities for sustainable food packaging through dimensions of industry 4.0: new insights into the food waste perspective. Trends Food Sci Technol 2023;142. https://doi.org/10.1016/j.tifs.2023.104238.
[145] Wu Q, Ding M, Guo J, Nie M, Wang Q, Wu L. Layer-by-layer stacking, low-temperature welding strategy to effectively recycle biaxially-oriented polypropylene film waste. Polymer (Guildf) 2022;253. https://doi.org/10.1016/j.polymer.2022.125006.
[146] Wang J, Guo H, Zeng S, Du J, Zhang Q, Wang K. Thin, largescale processed, high-temperature resistant capacitor films based on polypropylene/cycloolefin copolymer blend. Chem Eng J 2024;492. https://doi.org/10.1016/j.cej.2024.152237.
[147] Ding L, Zhang X, Wang Y. Study on the behavior of bopp film treated by corona discharge. Coatings 2020;10:1–11. https://doi.org/10.3390/coatings10121195.
[148] Usha ZR, Babiker DMD, Yu R, Yang J, Chen W, Chen X, Li L. Super hydrophilic modified biaxially oriented polypropylene microporous membrane for excellent gravity-driven oil/water emulsion separation. J Membr Sci 2022;660. https://doi.org/10.1016/j.memsci.2022.120840.
[149] Ilhan I, ten Klooster R, Gibson I. Observing the effect of pressure and temperature on the seal integrity of critical seal regions of various flexible bag designs. Food Packag Shelf Life 2023;37. https://doi.org/10.1016/j.fpsl.2023.101088.
[150] Zhang K, Yao J, Zhu F, Gao Y, Gu Y, Guo Y, Sun Y, An Y. Recent advances in preparation and application of BOPP film for energy storage and dielectric capacitors. Molecules 2025;30:1596. https://doi.org/10.3390/molecules30071596.
[151] Mostafavi AH, Mishra AK, Gallucci F, Kim JH, Ulbricht M, Coclite AM, Hosseini SS. Advances in surface modification and functionalization for tailoring the characteristics of thin films and membranes via chemical vapor deposition techniques. J Appl Polym Sci 2023;140. https://doi.org/10.1002/app.53720.
[152] Wieszczycka K, Staszak K, Woźniak-Budych MJ, Litowczenko J, Maciejewska BM, Jurga S. Surface functionalization – the way for advanced applications of smart materials. Coord Chem Rev 2021;436. https://doi.org/10.1016/j.ccr.2021.213846.
[153] Xie Z, Liu D, Tang X, Fu Z, Wang K, Zhang Q, Wang J, Fu Q. Largely improved dielectric energy performances and safety of BOPP film via surface engineering. Compos Sci Technol 2023;232. https://doi.org/10.1016/j.compscitech.2022.109856.
[154] Goyal M, Singh K, Bhatnagar N. Conductive polymers: a multipurpose material for protecting coating. Prog Org Coating 2024;187. https://doi.org/10.1016/j.porgcoat.2023.108083.
[155] Kim I, Viswanathan K, Kasi G, Thanakkasaranee S, Sadeghi K, Seo J. ZnO nanostructures in active antibacterial food packaging: preparation methods, antimicrobial mechanisms, safety issues, future prospects, and challenges. Food Rev Int 2022;38:537–65. https://doi.org/10.1080/87559129.2020.1737709.
[156] Lombo Vidal O, Tsukui A, Garrett R, Miguez Rocha-Leão MH, Piler Carvalho CW, Pereira Freitas S, Moraes de Rezende C, Simões Larraz Ferreira M. Production of bioactive films of carboxymethyl cellulose enriched with green coffee oil and its residues. Int J Biol Macromol 2020;146:730–8. https://doi.org/10.1016/j.ijbiomac.2019.10.123.
[157] Viswanathan VP, Kulandhaivelu SV, Manivasakan K, Ramakrishnan R. Development of biodegradable packaging films from carboxymethyl cellulose and oxidised natural rubber latex. Int J Biol Macromol 2024;262. https://doi.org/10.1016/j.ijbiomac.2024.129980.
[158] Mohamad Zulkifli NAS, Ng K, Ang BC, Muhamad F. Fabrication of water-stable soy protein isolate (SPI)/carboxymethyl cellulose (CMC) scaffold sourced from oil palm empty fruit bunch (OPEFB) for bone tissue engineering. Ind Crops Prod 2025;224. https://doi.org/10.1016/j.indcrop.2024.120325.
[159] Calosi M, D'Iorio A, Buratti E, Cortesi R, Franco S, Angelini R, Bertoldo M. Preparation of high-solid PLA waterborne dispersions with PEG-PLA-PEG block copolymer as surfactant and their use as hydrophobic coating on paper. Prog Org Coating 2024;193. https://doi.org/10.1016/j.porgcoat.2024.108541.
[160] Kumar P, Kudva S A, T AK, S R, Ramesh MR, Prabhu A, Anne G. Synthesis and characteristics of Fe/Ni/Cr oxide nanoparticles/PLA hybrid composite coatings on mg–zn–ca alloy. J Mater Res Technol 2025;35:2573–83. https://doi.org/10.1016/j.jmrt.2025.01.180.
[161] Zheng G, Han L, Zheng B, Bian J, Zhao Y, Pan H, Wang M, Zhang H. Enhanced strength, toughness and heat resistance of poly (lactic acid) with good transparency and biodegradability by uniaxial pre-stretching. Int J Biol Macromol 2024;278. https://doi.org/10.1016/j.ijbiomac.2024.135222.
[162] Wodag AF, Yang C, Islam MM, Islam MA, Zhou B, Raza M, Yimer TT, Wang Y, Xu F. Enhancing mechanical and thermal properties of three dimensional (3D) woven flax fiber/polylactic acid (PLA) green composites. Mater Today Commun 2025;46. https://doi.org/10.1016/j.mtcomm.2025.112833.
[163] Hadri SH, Tareen N, Hassan A, Naseer M, Ali K, Javed H. Alternatives to conventional plastics: polyhydroxyalkanoates (PHA) from microbial sources and recent approaches – a review. Process Saf Environ Prot 2025;195. https://doi.org/10.1016/j.psep.2025.106809.
[164] Grzebieniarz W, Biswas D, Roy S, Jamróz E. Advances in biopolymer-based multi-layer film preparations and food packaging applications. Food Packag Shelf Life 2023;35. https://doi.org/10.1016/j.fpsl.2023.101033.
[165] Iversen LJL, Rovina K, Vonnie JM, Matanjun P, Erna KH, 'Aqilah NMN, Felicia WXL, Funk AA. The emergence of edible and food-application coatings for food packaging: a review. Molecules 2022;27. https://doi.org/10.3390/molecules27175604.
[166] Priya K, Thirunavookarasu N, Chidanand DV. Recent advances in edible coating of food products and its legislations: a review. J Agric Food Res 2023;12. https://doi.org/10.1016/j.jafr.2023.100623.
[167] Rofeal M, Abdelmalek F. Evaluation of bioactive multilayer and edible gelatin/xanthan gels crosslinked with Echinacea purpurea for ricotta cheese preservation. Sustain Chem Pharm 2023;36. https://doi.org/10.1016/j.scp.2023.101322.
[168] Ureña M, Phùng TTT, Gerometta M, de Siqueira Oliveira L, Chanut J, Domenek S, Dole P, Roudaut G, Lagorce A, Karbowiak T. Potential of polysaccharides for food packaging applications. Part 1/2: an experimental review of the functional properties of polysaccharide coatings. Food Hydrocoll 2023;144. https://doi.org/10.1016/j.foodhyd.2023.108955.
[169] Li H, Xing R, Wang Z, Li G. Advancements in xanthan gum-based film and coating for food packaging. Carbohydr Polym 2025;356. https://doi.org/10.1016/j.carbpol.2025.123409.
[170] khosh goftar M, Bolandi M, Shariatifar N, Ziaolhagh S. Incorporation of whey protein with aqueous clove (Syzygium aromaticum L.) extract (nanoliposome and free forms) as an edible coating to prevent bacterial growth and oxidative spoilage of brown trout fillets. Food Control 2025;176:111386. https://doi.org/10.1016/j.foodcont.2025.111386.
[171] Payal A, Sandeep GDS, Bammidi M, Narayandas A, Syed I, Rao MV. Recent advances in plant protein-based edible coatings for shelf-life enhancement of perishable and high nutritive value foods – a review. Food Packag Shelf Life 2025;48. https://doi.org/10.1016/j.fpsl.2025.101465.
[172] Azizi M, Jahanbin K, Shariatifar N. Evaluation of whey protein coating containing nanoliposome dill (Anethum graveolens L.) essential oil on microbial,

physicochemical and sensory changes of rainbow trout fish. Food Chem X 2024; 21. https://doi.org/10.1016/j.fochx.2023.101110.
[173] Ahuja A, Kumar Rastogi V. Spray coating of edible insect waxes for liquid food packaging. Appl Surf Sci 2023;624. https://doi.org/10.1016/j.apsusc.2023.157150.
[174] Chaichi M, Badii F, Mohammadi A, Hashemi M. Novel bioactive composite films based on pectin-nanocellulose-synergistic triple essential oils: development and characterization. Food Bioprocess Technol 2023;16:1794–805. https://doi.org/10.1007/s11947-023-03036-x.
[175] Mendes JF, Norcino LB, Manrich A, Pinheiro ACM, Oliveira JE, Mattoso LHC. Characterization of pectin films integrated with cocoa butter by continuous casting: physical, thermal and barrier properties. J Polym Environ 2020;28: 2905–17. https://doi.org/10.1007/s10924-020-01829-1.
[176] Shabani M, Ghorbani-HasanSaraei A, Shariatifar N, Savadkoohi F, Shahidi SA. Effect of Urtica dioica L. essential oil (forms of free and nanoliposome) on some inoculated pathogens (Escherichia coli and Listeria monocytogenes) in minced camel meat. Food Chem 2023;X:20. https://doi.org/10.1016/j.fochx.2023.101050.
[177] Marzbani P, Azadfallah M, Yousefzadeh M, Najafi F, Pourbabaee AA, Koivula H, Ritala M. Effect of polyethylene wax/soy protein-based dispersion barrier coating on the physical, mechanical, and barrier characteristics of paperboards. J Coating Technol Res 2021;18:247–57. https://doi.org/10.1007/s11998-020-00403-7.
[178] Pouryousef N, Ahmady M, Shariatifar N, Jafarian S, Shahidi SA. The effects of essential oil Mentha pulegium L. and nisin (free and nanoliposome forms) on inoculated bacterial in minced silver carp fish (Hypophthalmichthys molitrix). J Food Meas Char 2022;16:3935–45. https://doi.org/10.1007/s11694-022-01514-y.
[179] Ahuja A, Rastogi VK. Shellac: from isolation to modification and its untapped potential in the packaging application. Sustainability 2023;15. https://doi.org/10.3390/su15043110.
[180] Shen T, Fan S, Li Y, Xu G, Fan W. Preparation of edible non-wettable coating with soybean wax for repelling liquid foods with little residue. Materials 2020;13. https://doi.org/10.3390/ma13153308.
[181] Udana Eranda DH, Chaijan M, Castro-Muñoz R. Current advances in surface wettability in food packaging materials: strategies, methods and future trends. J Food Eng 2025;391. https://doi.org/10.1016/j.jfoodeng.2024.112440.
[182] Rasheed M, Parveez B. Coating on packaging products to enhance shelf life. In: Biopolymers and biocomposites from agro-waste for packaging applications. Elsevier; 2021. p. 1–33. https://doi.org/10.1016/B978-0-12-819953-4.00012-4.
[183] Ju J, Zhao F, Vishnuvarthanan M. Regulations and laws related to use of edible coating and films. In: Edible film and coatings. Boca Raton: CRC Press; 2025. p. 418–36. https://doi.org/10.1201/9781032622354-20.
[184] Deshmukh RK, Gaikwad KK. Food packaging regulations and standards. In: Concepts of food packaging. New York: Apple Academic Press; 2025. p. 267–88. https://doi.org/10.1201/9781003597438-9.
[185] Bumbudsanpharoke N, Ko S. Nano-food packaging: an overview of market, migration research, and safety regulations. J Food Sci 2015;80. https://doi.org/10.1111/1750-3841.12861.
[186] Hu Y, Wang F, Zhao J, Ma S, Wang L. Recent advances in safety assessment of nanocellulose in food packaging. J Agric Food Chem 2025;73:28553–74. https://doi.org/10.1021/acs.jafc.5c08829.
[187] Olawore O, Ogunmola M, Desai S. Engineered nanomaterial coatings for food packaging: design, manufacturing, regulatory, and sustainability implications. Micromachines 2024;15:245. https://doi.org/10.3390/mi15020245.
[188] Jahangiri F, Mohanty AK, Misra M. Sustainable biodegradable coatings for food packaging: challenges and opportunities. Green Chem 2024;26:4934–74. https://doi.org/10.1039/D3GC02647G.
[189] Ji Y, Shen DE, Lu Y, Schueneman GT, Shofner ML, Meredith JC. Aqueous-based recycling of cellulose nanocrystal/chitin nanowhisker barrier coatings. ACS Sustainable Chem Eng 2023;11:10874–83. https://doi.org/10.1021/acssuschemeng.3c02457.
[190] Golkaram M, Mehta R, Zakarya S, Rytöluoto I, Prins L, Brouwer-Milovanovic M. Advancing circularity in multilayer film recycling: balancing quality and sustainability. Polymers 2025;17:2868. https://doi.org/10.3390/polym17212868.
[191] RecyClass. RecyClass online tool. https://tool.recyclass.eu/en/. [Accessed 30 September 2025].