REVIEW PAPER

Polyolefinic Materials in Packaging: Prospects and Environmental Threats: A Comprehensive Review

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ABSTRACT

The global packaging industry is primarily influenced by polyolefinic materials, such as polyethylene (PE) and polypropylene (PP), which offer a combination of durability, flexibility, and cost-effectiveness. These materials have transformed modern packaging through their lightweight offerings for food, medical, and industrial uses. The widespread employment of non-biodegradable plastics poses substantial challenges in waste management due to their persistent presence and significant contribution to plastic pollution. This review examines the characteristics, applications, and ecological implications of polyolefins, with a particular focus on their importance in packaging. This paper discusses recent advancements in biodegradable alternatives and chemical recycling methods, aiming to address the environmental challenges presented by plastic waste. Integrating natural fillers into polyolefin composites can boost biodegradability without compromising functionality. The review highlights the importance of a circular economy approach, which emphasizes sustainable practices for transforming polyolefin waste into valuable resources. This analysis explores the advantages and disadvantages of polyolefins to guide future research and sustainable packaging policy.

Keywords: polyolefins, packaging, environmental impact, recycling technologies, biodegradable alternatives.

Highlights

- This review evaluates the advantages and risks to the environment.
- Highlights the significance of creative solutions in packaging.
- Grasp of the opportunities and constraints related to polyolefinic packaging.
- Sustainability in the most current developments of contemporary packaging.

CONTENTS

INTRODUCTION

Polyolefinic materials— primarily polyethylene (PE) and polypropylene (PP)— are important in packaging because they are cost-effective, durable, and versatile [1]. Their extensive use has transformed packaging across several industries, including consumer items, medicines, industrial packaging, and food storage [2, 3]. They offer materials that increase product shelf life and boost transportation efficiency since they are lightweight, strong, and extremely secure. However, the widespread use of these non-biodegradable materials has led to serious environmental problems. Every year, millions of tons of garbage containing polyolefins are produced worldwide, much of which is disposed of in landfills, marine environments, and terrestrial ecosystems. The long-term buildup of plastic trash poses a major threat to biodiversity, soil and water quality, and the general health of ecosystems since PE and PP are resistant to natural degradation processes and do not easily decompose in the environment [4, 5]. According to recent research, polyolefin-based plastics are becoming a bigger source of plastic pollution worldwide. It is becoming more common to find microplastics and macroplastics made of packaging materials in freshwater environments, ocean eddies, and even the atmosphere. These materials serve as transporters of hazardous chemicals and persistent organic pollutants (POPs), in addition to physically damaging natural habitats and endangering wildlife by entangling or feeding on them [6, 7]. Now, both industry and researchers are focusing on solving these environmental problems. Although scalability and economic viability are still important barriers, recycling innovations such as advanced chemical and mechanical technologies are attempting to increase the reuse potential of polyolefins [8, 9].

RESEARCH BACKLOG

A major research area in the packaging research backlog of polyolefinic materials is effective and extensive recycling technologies, especially chemical recycling. Conventional methods for polyolefins are often limited by contamination and material degradation. The study highlights the need for bio-based polyolefin alternatives that can reduce dependence on fossil fuels; However, these options still need improvement to meet industry sustainability and energy standards. Understanding the environmental effects and degradation processes of polyolefins in natural environments, particularly their transformation into microplastics, which have major consequences for marine life and ecosystem health, is another important area. The importance of consumer awareness and regulatory legislation in developing sustainable packaging practices is also receiving increasing attention; Research indicates that these two elements may encourage the adoption of a circular model for plastic use. Finally, to promote circularity and reduce waste, research is needed on developing effective closed-loop solutions in the packaging sector. By filling these research gaps, polyolefin packaging will be placed within the framework of a circular economy, which balances functional benefits with environmental responsibility while also promoting environmental sustainability.

OBJECTIVE

This review evaluates the advantages, risks to the environment, and most current developments in sustainable practices of polyolefinic materials used in contemporary packaging. This study seeks to give a thorough grasp of the opportunities and constraints related to polyolefinic packaging by analysing recent studies and market trends. It highlights the significance of creative solutions to lessen the packaging's negative environmental effects.

POLYILEFINIC MATERIALS IN PACKAGING: AN OVERVIEW

History of innovations and current global production status

The history of innovation in polyolefin packaging reflects a journey that bears witness to advances in materials science driven by the demand for cost-efficiency, durability, and performance. Polyolefins—primarily polyethylene (PE) and polypropylene (PP)— emerged as the dominant packaging material in the mid-20th century, due to their lightweight, chemical resistance, and versatile uses [10]. In the 1950s–60s, high-density polyethylene (HDPE) began to be used for rigid containers and low-density polyethylene (LDPE) for flexible films, while in the 1970s, linear low-density polyethylene (LLDPE) was introduced, providing greater rigidity for stretch films and bags. In the 1980s–90s, metallocene catalysis was introduced, enabling the synthesis of precision polymers for greater strength and clarity. The timeline of innovations in polyolefinic production is depicted in Figure 1 [11, 12]. Rapid advances in processing technology and material change over the past few decades are directly responsible for the global production and market dominance of polyolefins in the modern packaging industry. Currently, polyolefins cover a significant portion of the global plastics market, with the packaging sector being the largest user of the material [13]. The Asia-Pacific region currently leads the world in production, followed by North America and Europe. Emerging markets in the Middle East, Africa, and South America are also continuing to increase production capacity due to infrastructure development and expansion of the retail sector. Globally, the packaging industry is the largest consumer of polyolefins, accounting for more than 40% of total consumption, and is currently placing increasing emphasis on recyclable and sustainable packaging solutions [14,15]. An overview of the global production distribution is presented in Table 1.

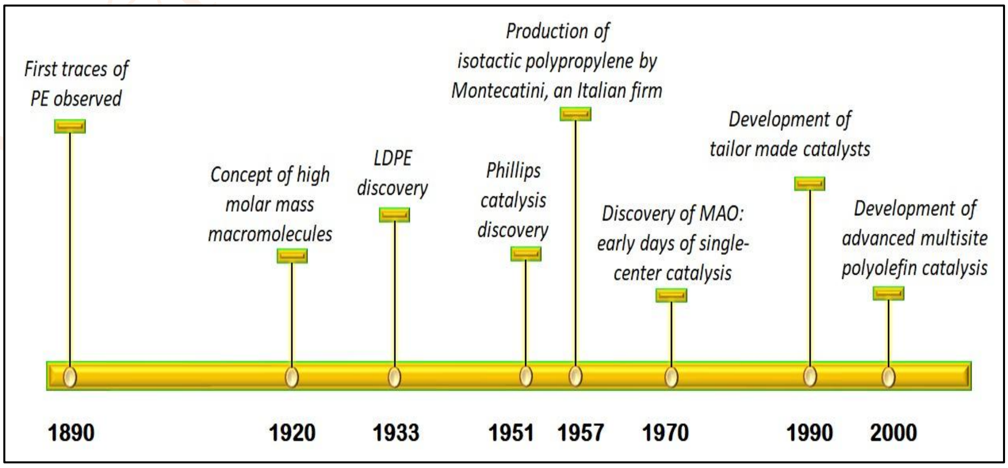

Figure 1. Timeline of innovations in polyolefinic packaging. Image adapted with permission from Ref. [11]. Copyright 2017 by the authors. Licensee MDPI, Basel, Switzerland.

Table 1. Current worldwide production status of polyolefinic packaging.

Countries	% of production	Major applications	Ref.
North America	24	Packaging, automotive, electronics, agriculture, construction materials, healthcare, and consumer goods.	[16]
Japan	6.5	Food packaging, shrink film, industrial, consumer goods, and pharmaceutical packaging.	[17]
Africa, Middle East	6	Film & sheet, injection molding, blow molding, fibers & raffia	[18]
Asia (without Japan)	30	Food packaging, industrial, consumer goods, and pharmaceutical packaging, retail (from clothing to toys), and E-commerce packaging	[19]
South America	4.5	Automotive, healthcare, pipes & fittings	[20]
Other EU25+N/CH	3.5	Food packaging (by LDPE, LLDPE, and HDPE), blend materials (emphasizing degradation properties).	[21]
Benelux	5	Food and pharmaceutical packaging, manual, semi-automatic, and automatic packaging, industrial, electronics, and textile packaging.	[22]
France	3	Medical, automotive, food, consumer goods, and cosmetics packaging.	[23]
Italy	2	Textile industry, plastic recycling	[24]
UK	1.8	Automotive. Construction. Textiles, Medical	[25]
Spain	1.7	Packaging industry, Fibrous Ion-Exchange Material (water treatment, chemical processing), water pollution mitigation	[26]
Germany	8	Automotive industry, textile industry, medical and healthcare, building and construction, electronics	[27]
Other Europe	4	Agriculture (greenhouse covers, mulching films, and irrigation pipes), the automotive industry, and the general plastic products making.	[28]

Characteristics of polyolefinic materials

A polymer having the general formula $(CH_2CHR)_n$, where R is an alkyl group, is called a polyolefin [29]. The two most widely used polyolefins are polyethylene and polypropylene. Specialized polyolefins also include polymethyl pentene and polyisobutylene. These materials are usually hard thermoplastics, and their transparency can range from opaque to translucent, depending on the type. Polyethylene (PE), especially the high-density type (HDPE), is usually opaque due to its crystalline structure. Low-density polyethylene (LDPE) and polypropylene (PP) can appear somewhat translucent depending on processing and thickness. Polymethylpentene (PMP), although a polyolefin, is known for its high transparency and is used where transparency is required [30]. Thus, while some specialty types of polyolefins can approach transparency, most polyolefins are not truly transparent and should not generally be described as such. Because polyolefins are chemically inert, acids, alkalis, and other chemicals cannot cause them to corrode. Because polyolefin fibers are lighter than steel fibers, they can be used in situations where weight is a concern [31,32]. Low water absorption contributes to the strength and weather resistance of polyolefin materials. Since polyolefins often have high melting points and good thermal stability, they can be used in applications that require resistance to heat. Because of their superior thermal insulation qualities, polyolefins are perfect for use in electrical and electronic applications. Because polyolefin fibers are stretchable and flexible, they can be used in a wide range of applications where resilience and impact resistance are necessary. The synthesis of polyolefins or their blends with natural resins offers the potential to produce environmentally friendly polymer products [33].

Applications of common types of polyolefins in the packaging industry

Polyethylene (PE)

The thermoplastic polymer polyethylene (PE) is a multipurpose material with favorable properties and low cost that finds widespread application in various industries. Depending on its density and molecular structure, it is divided into several types [34]. The polymer polyethylene family includes low-density polyethylene (LDPE), medium-density polyethylene (MDPE), high-density polyethylene (HDPE), linear low-density polyethylene (LLDPE), cross-linked polyethylene (XLPE), and ultra-high molecular weight polyethylene (UHMWPE). HDXLPE stands for high-density cross-linked polyethylene, HMWPE for high molecular weight, and ULMWPE or PE-WAX for ultra-low molecular weight polyethylene. They are all different in what they offer and how they can be used [35-37]. High-density polyethylene (HDPE) is typically used for rigid containers, bottles, and lids, whereas low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE) are commonly employed for flexible films, bags, and wraps [38].

Polypropylene (PP)

Polypropylene (PP) is a versatile thermoplastic polymer that is widely used in a variety of industries due to its superior properties and low cost. It includes several types, each designed for a specific application [39]. Homopolymer Polypropylene (PP-H) is an ideal material for automotive parts and packaging due to its high stiffness and strength. Random Copolymer Polypropylene (PP-R) is a flexible and impact-resistant material that is widely used in food packaging and medical devices [40-42]. Impact Copolymer Polypropylene (PP-I) has higher impact strength and is ideal for automotive bumpers and containers. Polypropylene Composite (PP-C) reinforces mechanical properties and is used in automotive components and construction materials. High-melt-strength polypropylene (HMS-PP) is used in foam extrusion, automotive interiors, and insulation [43,44]. Polypropylene is popular for its excellent transparency, high melting point, and toughness, which makes it suitable for food packaging, microwavable containers, and labelling films [45]. These materials help to extend the shelf life of products, ensure safety during transportation, and reduce overall packaging costs. These attributes, which include density, melting temperature, tensile strength, elongation at break, barrier performance, transparency, and flexibility, are contrasted in Table 2, showing how material parameters influence choices for certain applications in the packaging sector.

Table 2. Properties of common polyolefinic materials used in packaging.

Comparative features	Polyethylene	Polypropylene	Ref.
Chemical composition	Repeated ethylene monomer units (-CH_3-CH_3-) derived from petroleum or natural gas.	Repeated propylene monomer units (-CH_2-$CH(CH_3)$-) derived from petroleum.	[46]
Types	Low-density polyethylene (LDPE), Medium-density polyethylene (MDPE), High-density polyethylene (HDPE), Linear low-density polyethylene (LLDPE), etc.	Homopolymer polypropylene, Random copolymer polypropylene, Block copolymer polypropylene, Thermoplastic olefin (TPO).	[47]
Density (g/cm³)	0.91-0.94 g/cm³	0.90 to 0.91 g/cm³	[48]
Melting Point (°C)	115-135°C	130-171°C	[49]
Tensile Strength (MPa)	8–32 MPa	30–50 MPa	[50]
Elongation at Break (%)	100–600% (LDPE/LLDPE higher than HDPE)	200–700% (varies with grade and processing)	[51]
Barrier Performance	Excellent moisture barrier, but poor gas (oxygen/CO_2) barrier	Good moisture barrier, but moderate to poor oxygen and aroma barrier	[52]
Transparency	Transparent or translucent	Mostly translucent	[53]
Flexibility	Partially flexible	Mostly rigid and stiff	[54]
Applications	Used in packaging films, bottles, pipes, and consumer goods due to its flexibility and moisture resistance.	Often used in packaging, medical equipment, automotive parts, and textiles because of its strength, rigidity, and resistance to heat.	[55]

Advantages of polyolefinic packaging materials

Polyethylene and polypropylene are two examples of polyolefinic packaging materials that offer several benefits for various packaging applications. Their exceptional barrier qualities against moisture, gases, and pollutants ensure the preservation of the quality and freshness of packaged goods. They are also flexible enough to accommodate a wide range of packaging requirements. Polyolefins, especially those used in food packaging, have low surface energies, making them ideal for uses where adhesion must be prevented. In addition, their affordability with substitutes is a factor in their extensive application in various sectors [56]. Furthermore, some compositions based on polyolefins are biodegradable, providing packaging options that are friendly to the environment. They include polymers such as polylactic acid (PLA) [57], polyhydroxyalkanoates (PHA) [58], starch-based plastics [59], cellulose-based plastics [60], and protein-based plastics [61,62]. Moreover, the processing of polyolefin films produces no hazardous fumes, which makes them sustainable and safe for use in a variety of applications. The versatility, barrier qualities, affordability, environmental advantages, safety, and sustainability of polyolefinic packaging materials make them an appealing option for packaging overall [63].

PROSPECTS OF POLYOLEFINIC MATERIALS IN PACKAGING

Innovations in polyolefinic packaging

Increasing sustainability, recyclability, and overall efficiency are the main goals of polyolefin packaging innovation as a result of regulatory pressures and environmental concerns. The creation of recyclable and biodegradable materials, enhancements to mechanical and functional qualities, and circular economy initiatives are noteworthy developments [64]. Prominent corporations like Dow Chemical and Braskem have created bio-based polyolefin materials. One such product is Braskem's I'm green™ polyethylene (PE), which is made from sugarcane ethanol and offers a sustainable substitute for traditional petroleum-based polymers. Furthermore, BASF's ecovio® and TotalEnergies' RE:clic™ flexible polyolefins stand out for improving packaging applications for recycling and composting.

Borealis and LyondellBasell have created sophisticated polyolefins like Borstar® and Hostalen® that offer lightweight and long-lasting packaging solutions while preserving a balance between strength and flexibility in terms of enhancing mechanical and functional qualities. Furthermore, food-grade packaging materials' sealability, optical clarity, and puncture resistance have all been enhanced by ExxonMobil's Exceed™ S metallocene PE. SABIC's TRUCIRCLE™ program has led the way in the use of chemically recycled polyolefins for packaging applications, thereby promoting circular economy objectives. In the meantime, businesses like Loop Industries and PureCycle Technologies have created mechanical recycling techniques that enable the production of premium recycled PET and PP that are appropriate for high-efficiency applications. To lessen dependency on fossil fuel-based feedstocks, package makers are collaborating with startups like Neste and Origin Materials to integrate bio-naphtha and other renewable hydrocarbons into the polyolefin production process. Recent scholarly studies have also emphasized how crucial it is to have a consistent waste stream to optimize the potential of recycled polyolefins for usage in both rigid and flexible packaging applications. Researchers are also working on polymer composites that include bio-based additives, cellulose nanofibers, and nanoclays to enhance the physicochemical and barrier qualities of polyolefin films. The recent innovations in packaging are listed in Table 3.

Table 3. Recent Innovations in Packaging.

Innovation Area	Description	Benefits	Ref.
Bio-based Polyolefins	Derived from renewable sources like sugarcane or corn	Minimizes reliance on fossil fuels, and biodegradable alternatives are becoming more available.	[65]
Recyclable Mono-material Films	Packaging made from a single polymer type (e.g., all-PE or all-PP)	Easier to recycle, improves circularity in waste streams	[66]
Nanocomposite Barriers	Use of nanoclays or nanosilica to enhance film barrier properties	Extends shelf life by improving moisture and gas resistance	[67]
Active Packaging	Incorporates antimicrobial agents or oxygen scavengers	Increases food safety and freshness	[68]
Intelligent Packaging	Uses sensors or indicators to monitor product condition (e.g., freshness tags)	Provides real-time quality info, enhances consumer trust	[64]
Edible Packaging	Made from edible films like starch, proteins, or seaweed	Reduces waste; safe and biodegradable	[69]
Water-soluble Packaging	Dissolves in water; used for single-use applications	Minimizes waste, especially for hygiene or cleaning products	[70]
Chemical Recycling Technologies	Breaks down polymers into monomers or fuels using pyrolysis/gasification	Allows the reuse of plastic waste that's hard to mechanically recycle	[71]
Compostable Laminates	Multi-layer structures that decompose under composting conditions	Suitable for eco-friendly, disposable applications	[72]
3D-Printed Packaging Prototypes	Rapid prototyping using 3D printing for custom packaging designs	Reduces development time, improves customization, and innovation	[73]

Moving towards responsible and limited use of polyolefins in packaging

While polyolefin materials such as polyethylene (PE) and polypropylene (PP) are important in the packaging industry due to their low cost and sustainable properties, environmental concerns require a more responsible approach to their use [74]. The overuse of these organic-nonbiodegradable materials causes a huge amount of plastic pollution every year, especially in landfills and marine environments. Therefore, the main goal of research and innovation should not only be to increase the performance of polyolefins, but also to limit their use or focus on environmentally friendly alternatives [75].

An important strategy is to create bio-based or biodegradable blends, where polyolefins are combined with materials such as starch, PLA, or cellulose to reduce the environmental impact. In addition, lightweighting, packaging made from recyclable single-material materials, and increasing the adoption of closed-loop systems are very important steps for sustainability. Additionally, regulatory policies and consumer awareness programs play an important role in encouraging more sustainable packaging practices instead of the traditional use of polyolefins [76].

Trends and future directions

Polyolefinic materials, such as polyethylene and polypropylene, are undergoing significant advancements in packaging applications, with a focus on sustainability, functionality, and performance improvements [77]. Researchers are prioritizing the development of biodegradable and sustainable polyolefin-based packaging solutions to align with global environmental trends. Additionally, there is a rising interest in functional packaging, leading to the integration of active and intelligent features like antimicrobial properties and smart sensors for enhanced product safety and quality monitoring [78]. Smart packaging features are also being added to keep food fresh or show if it has spoiled [79]. Circular economy initiatives are driving the development of polyolefin materials compatible with closed-loop systems, aiming to optimize recycling processes and promote material reuse. Moreover, ongoing research aims to enhance the barrier properties of polyolefin-based packaging through nanotechnology and advanced coating techniques to prolong shelf life and preserve product freshness. These efforts underscore the continuous innovation in polyolefinic materials, catering to evolving consumer preferences and industry requirements in the packaging sector [80,81].

ENVIRONMENTAL IMPACT OF POLYOLEFINIC PACKAGING

Contribution to plastic pollution

Packaging made from polyolefinic materials is a significant source of plastic pollution due to its extensive use and environmental persistence. Studies suggest that compositions based on polyolefins, which are recognized for their resilience to environmental conditions, exacerbate the problem of plastic pollution by facilitating the build-up of non-biodegradable waste. Plastic packaging, including materials based on polyolefin, still contributes significantly to environmental effects even though it makes up less than 10% of the life cycle emissions of many food products [82]. Even though it is advantageous, the recycling of waste polyolefins into other materials highlights the environmental issues associated with polyolefinic packaging and the demand for sustainable substitutes. Environmental problems are made worse by the high stability and resistance to deterioration of polyolefin materials, which leads to an increase in pollution and landfills. Environmental consequences resulting from the degradation of plastic, particularly polyolefins, underscore the pressing need for efficient waste management plans and environmentally friendly packaging substitutes to reduce plastic pollution and protect the environment [83]. A comparative environmental effect assessment of the most widely used polyolefinic materials in packaging is shown in Table 4. It draws attention to how differently polyethylene and polypropylene perform in terms of parameters.

Table 4. Environmental impact assessment of polyolefinic packaging.

Environmental impact category	Description	Impact assessment for polyolefinic packaging	Ref.
Greenhouse Gas Emissions	Results in global warming due to the emission of greenhouse gases (CO_2, CH_4)	During raw material extraction, manufacturing, and transportation, polyolefinic packaging emits greenhouse gases.	[84]
Energy Consumption	Consumption of energy in total throughout the life cycle of packaging	Energy is required during extraction, refining, processing, and transportation	[85]
Water Usage	Water consumption in total. Includes both direct and indirect water uses.	Unlike paper or glass, polyolefinic packaging material has typically low water consumption.	[86]
Resource Depletion	Depletion of non-renewable energy resources such as fossil fuels and materials.	Raw material includes crude oil during the production of polyolefin packaging materials	[87]
Waste Generation	Generation of waste throughout the life cycle, including production waste and end-of-life disposal.	Solid waste is produced if not properly disposed of or recycled.	[88]
Air Pollution	Air pollution is emitted into the atmosphere during production and transportation	Polyolefinic packaging production can contribute to air pollution through emissions from manufacturing processes and transportation.	[89]
Water Pollution	Water bodies get contaminated by the production process or leaching of chemicals.	Discharge of pollutants during the manufacturing of polyolefinic packaging material results in water pollution.	[90]
Ecotoxicity	Toxic effects on ecosystems and wildlife due to chemical releases.	Polyolefinic packaging materials can leach chemicals into the environment, potentially affecting aquatic and terrestrial ecosystems.	[91]
Human Health Impacts	Health effects on workers and communities exposed to production processes and pollutants.	Polyolefinic packaging production may pose health risks to workers due to exposure to chemicals and pollutants.	[92]

Challenges in recycling and degradation

Recycling and degradation of polyolefin polymers, such as polypropylene (PP) and polyethylene (PE), are extremely difficult because of their distinct chemical and physical characteristics. These polymers are very resistant to biological and environmental degradation processes because of their crystalline structure, large molecular weight, and hydrophobic nature [93]. Traditional mechanical recycling methods have problems with material contamination, property deterioration from repeated reprocessing, and the inability to separate polymers that have been enhanced with various additions and components [94, 95]. Chemical recycling can recover monomers and create high-quality materials, but it is expensive, energy-intensive, and has limitations when used on a large scale. Furthermore, polyolefins do not naturally degrade because of their resistance to oxidation, UV light, and microbial attack. As a result, these plastics accumulate in the environment for extended periods. The recycling process is further complicated by the extensive use of additives and multi-layer packaging methods, which impair the processing and purity of recycled materials [72, 96]. Better material design, cutting-edge sorting technologies, scalable chemical recycling procedures, and the creation of additives or bio-based catalysts that can speed up deterioration in regulated conditions are all necessary to overcome these problems.

Polyolefin waste contamination is a significant barrier to degradation and recycling. The quality of the recycled product is decreased by food residues, colours, adhesives, and multi-layer packaging materials, which make it challenging to separate the components. These contaminants have the potential to degrade recycling apparatus, impair polymer performance, and generate hazardous byproducts during the degradation process. Therefore, to improve the effectiveness and safety of recycling and degradation processes, contamination control is essential, as depicted in Figure 2 [97].

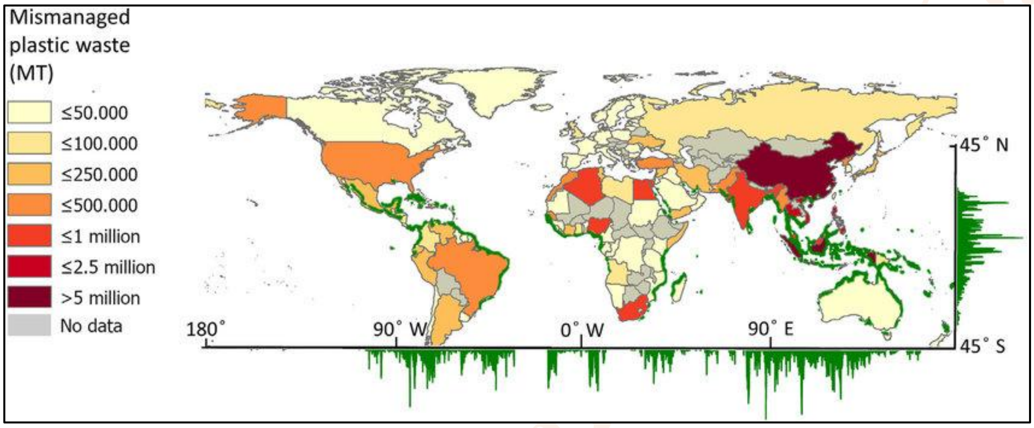

Figure 2: Global management of polyolefinic materials. Image reproduced with permission from Ref. [99]. Copyright 2020 The Authors. Published by Elsevier B.V.

Environmental regulations and policies

Addressing the effects of polyolefinic packaging on the environment requires the implementation of environmental regulations and policies. The study emphasizes the need for more stringent laws to lessen the damaging environmental effects of polyolefin packaging. Promoting sustainable practices in the packaging sector requires policies that prioritize recycling, waste management, and the circular economy. Furthermore, a call to action has been made to lessen the environmental impact of packaging systems, highlighting the significance of implementing eco-friendly materials and technologies [98]. Governments can reduce the environmental impact of polyolefinic packaging by enacting comprehensive regulations and policies that encourage the adoption of eco-friendly alternatives, support recycling initiatives, and spur innovation toward more sustainable packaging solutions. The lifecycle of polyolefinic packaging is depicted in Figure 3 [99].

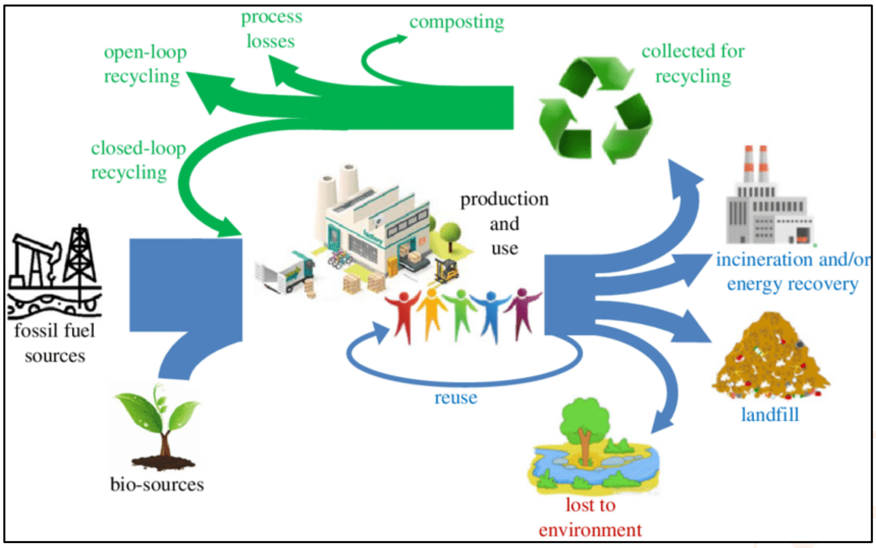

Figure 3. Life cycle of polyolefin packaging. Image reproduced with permission from Ref. [101] Copyright 2020 The Author(s).

MITIGATING ENVIRONMENTAL THREATS

Advances in biodegradable polyolefins

The development of biodegradable polyolefins has advanced significantly in recent years, providing promising solutions to reduce the environmental risks associated with conventional polyolefin packaging materials. Research demonstrates how new processing methods and formulations can improve polyolefins' biodegradability. Through the facilitation of their degradation through natural processes, these advancements seek to address the concerns regarding the persistence of packaging waste based on polyolefins in the environment [100]. Researchers highlight how biodegradable polyolefins can improve the environment by lowering carbon footprints and encouraging resource regeneration. In addition, research is currently being conducted to examine the characteristics and potential uses of these novel materials, which could lead to their extensive integration into a variety of sectors, including packaging. A significant step toward accomplishing sustainability objectives and reducing the environmental impact of packaging materials is represented by these developments in biodegradable polyolefins [101]. Table 5 compiles recent advancements in the development of biodegradable polyolefins.

Table 5. Advancements in Biodegradable Polyolefins.

Advancement Area	Description	Examples	Benefits	Ref.
Blending with Biodegradable Polymers	Polyolefins are blended with starch, PLA, PHA, or other biodegradable polymers.	PE/starch blends, PP/PLA blends	Enhanced biodegradability, cost-effective	[102]
Oxo-biodegradable Additives	Addition of pro-oxidant additives that initiate degradation under UV or heat.	PE with d2w™, TDPA™	Promotes fragmentation followed by microbial degradation	[103]
Enzymatic Surface Modifications	Enzymes are used to modify the surface to increase microbial attack.	PE treated with lipase or cutinase	Initiates surface degradation, improves compostability	[104]
Grafting Biodegradable Chains	Biodegradable polymers grafted onto a polyolefin backbone.	Maleic anhydride-grafted PP with PCL or PLA	Maintains strength, improves environmental compatibility	[105]
Photodegradable and UV-sensitive Films	Films modified to break down under sunlight exposure.	PE films with titanium dioxide (TiO_2) or benzophenone groups	Useful for agricultural mulch or outdoor applications	[106]
Microbial-degradable Polyolefins	Polyolefins engineered or modified to be more attractive to microorganisms.	PE with bio-nano additives or surfactants	Accelerates microbial colonization and degradation	[107]
Copolymerization Approaches	Synthesis of new copolymers incorporating biodegradable units.	PE-co-PCL, PP-co-PLA	Tailored degradation rates and mechanical performance	[108]
Nanocomposite Integration	Use of nanoclays or nanosilica to support controlled degradation.	Starch/nanoclay/PP blends	Enhances both biodegradability and barrier/mechanical traits	[109]

Introduction of alternatives to polyolefinic packaging

To reduce environmental impacts and produce sustainable environmental packaging solutions, alternative materials are introduced:

Paper-based packaging

Packaging made from paper and paperboard materials, sourced from renewable wood fibers.

Advantages: Biodegradable, recyclable, and renewable. It can be produced from sustainably managed forests.

Applications: Carton boxes, corrugated packaging, paper bags, moulded pulp trays [110].

Bioplastics

Plastics derived from renewable biomass sources such as corn starch, sugarcane, or cellulose.

Advantages: Biodegradable, compostable, and potentially carbon-neutral if sourced sustainably.

Applications: Biodegradable films, food packaging, compostable bags, disposable cutlery [111].

Glass packaging

Packaging made from glass, a natural and infinitely recyclable material.

Advantages: Fully recyclable, inert, and preserves product quality without leaching chemicals.

Applications: Bottles, jars, containers for food and beverages, cosmetic products [112].

Metal packaging

Packaging made from aluminium or steel, known for its durability and recyclability.

Advantages: Infinitely recyclable without loss of quality, lightweight, and offers excellent barrier properties.

Applications: Aluminium cans, foil packaging, metal bottles, aerosol containers [113].

Biodegradable and compostable packaging

Packaging materials are designed to break down into natural elements under specific conditions.

Advantages: Reduce landfill waste, can be composted to enrich soil, and reduce dependency on fossil-based plastics.

Applications: Biodegradable plastic films, compostable food packaging, cutlery, food containers [114].

Reusable packaging

Packaging is designed for multiple uses, reducing the need for single-use items.

Advantages: Reduces waste generation, conserves resources, and often results in cost savings over time.

Applications: Reusable shopping bags, glass or metal containers for food storage, refillable beverage containers [115].

Recycling technologies and circular economy approaches

To mitigate the environmental effects of polyolefinic packaging, recycling technologies and circular economy strategies are essential. Resource recovery is facilitated by the efficient separation and recycling of polyolefin-based materials made possible by advanced sorting and processing techniques. Polyolefins can be broken down into reusable products through chemical recycling techniques like depolymerization and pyrolysis, which promote circularity [116]. To minimize waste and lessen dependency on virgin resources, closed-loop systems encourage the collection, recycling, and reintegration of packaging made of polyolefin. Furthermore, encouraging laws and rules encourage recycling practices, which promote sustainability. The aforementioned strategies underscore the importance of innovation, policy implementation, and cooperative endeavours to foster sustainable practices in polyolefin packaging and progress toward a circular economy [117, 118]. As depicted in

Figure 4, it describes the plastic waste recycling methods are generally divided into four categories: primary, secondary, tertiary, and quaternary [118]. Primary recycling is the conversion of clean and uncontaminated plastic into a product of the same type with minimal modification. Secondary recycling is the conversion of slightly contaminated plastic into a lower-quality product by mechanical processing. Tertiary recycling, also known as chemical recycling, involves breaking down plastic into chemical components or fuels. These processes include chemical recovery, pyrolysis, gasification, and hydrogenation— some of which use homogeneous or heterogeneous catalysts. Finally, quaternary recycling is energy recovery, where plastic waste is burned to produce energy, although this is environmentally hazardous. These methods represent different approaches to plastic waste management, with increasing complexity and energy consumption from primary to quaternary [119, 120]. The recycling rates and methods for polyolefin materials are summarized in Table 6.

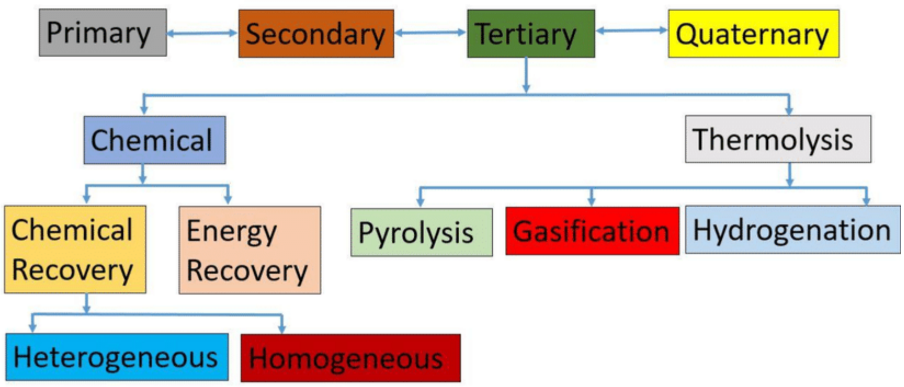

Figure 4. Flow chart of waste particle recycling process. Image reproduced with permission from Ref. [118]. Copyright 2020 by the authors. Licensee MDPI, Basel, Switzerland.

Table 6. Recycling rates and methods for polyolefin materials. The rate of recycling of polyolefin materials is less than 20%.

Region	PE recycling rate (%)	PP recycling rate (%)	Notes	Ref.
Europe	30-40	30-40	Europe has relatively high recycling rates due to stringent EU directives and commitments towards circular economy goals.	[121]
North America	10-15	10-15	The US and Canada have lower recycling rates, but there are ongoing efforts to improve infrastructure and public participation in recycling programs.	[122]
Asia-Pacific	20-30	20-30	Varies widely across countries; some, like Japan and South Korea, have higher rates due to advanced waste management systems.	[123]
Latin America	<10	<10	Recycling infrastructure is still developing in many countries, leading to lower recycling rates.	[124]
Middle East & Africa	<5	<5	Generally low due to limited recycling infrastructure and public awareness, though there are initiatives aiming to change this.	[125]

Mechanical recycling

In this case, the recycling of plastic is done by reprocessing the plastic without structural alteration. The process steps, output quality, and applications of recycled materials are provided in Table 7.

Table 7. Mechanical recycling of polyolefins.

Material	Input	Process steps	Output quality	Applications of recycled material	Ref.
PET	Beverages, bottles, and packaging	Sorting, grinding, washing, drying, re-melting, pelletizing	High quality if sorted and cleaned effectively; may degrade with repeated recycling	Fibers (e.g., carpets, clothing), new bottles, food containers	[126]
HDPE	Milk jugs, detergent bottles	Sorting, shredding, washing, granulating, re-melting, pelletizing	Can retain high quality with proper sorting and cleaning; slight degradation over cycles	Non-food bottles and containers, pipes, lumber, and benches	[127]
LDPE/LLDPE	Plastic films, bags, wraps	Sorting, washing, drying, agglomerating (if necessary), re-melting, pelletizing	Quality varies; often downcycled due to contamination and collection issues	Trash bags, construction films, wood-plastic composites	[128]
PP (Polypropylene)	Food containers, automotive parts, textiles	Sorting, grinding, washing, drying, re-melting, pelletizing	High quality if properly sorted and cleaned; susceptible to degradation with repeated recycling	Automotive parts, garden products, buckets, and crates	[129]
PS (Polystyrene)	Disposable cutlery, CD cases	Sorting, cleaning, compacting, re-melting, pelletizing	Generally lower quality; often downcycled	Insulation, picture frames, and stationery items	[94]
PVC (Polyvinyl Chloride)	Window frames, pipes, cable insulation	Sorting, grinding, washing, drying, re-melting, pelletizing	Quality depends heavily on the removal of additives and contaminants	Pipes, flooring, garden hoses, mudflaps	[130]
Mixed Plastics	Various mixed plastic items	Manual or automated sorting (often challenging), washing, compatibility, pelletizing	Lower quality due to mixing of polymers; applications limited to less demanding products	Lumber, outdoor furniture, decking	[131]

Chemical recycling techniques of polyolefins

Chemical recycling of polyolefins is a new technique that involves the breaking of polymers into corresponding monomers. As a result of this, new materials are produced from the old without degradation in quality [132]. The methods involved in chemical recycling are a) Pyrolysis, b)

Gasification, and c) Chemolysis, as depicted in Figure 5. The techniques for chemical recycling of polyolefins are listed in Table 8.

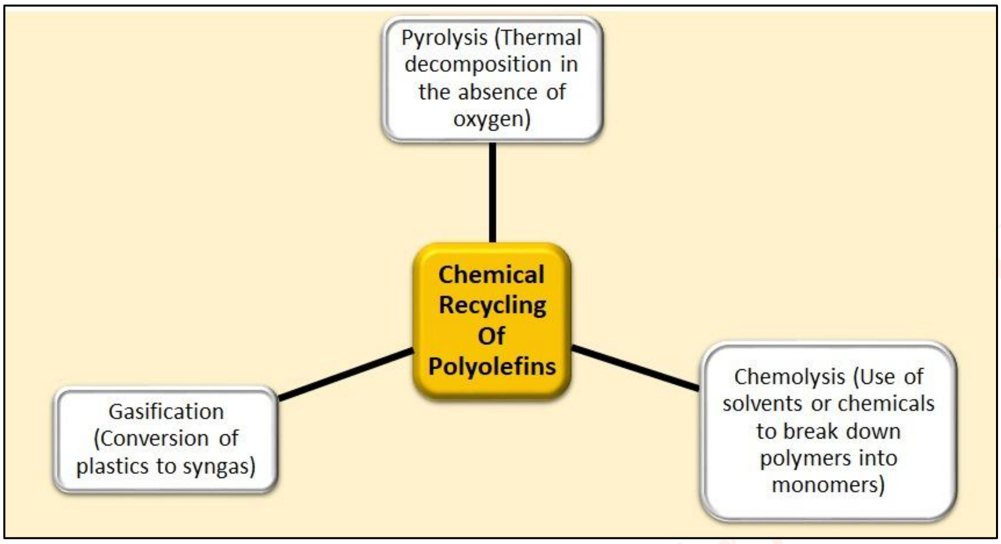

Figure 5. Chemical Recycling of Polyolefins.

Table 8. Chemical recycling of polyolefins.

Technology	Typical inputs	Process description	Outputs	Advances	Challenges	Ref.
Pyrolysis	Mixed PE, PP	Thermal decomposition in the absence of oxygen, converts plastics into a pyrolysis oil that can be used as a feedstock for new plastics or as fuel.	Pyrolysis oil, gas, wax	Can handle mixed and contaminated waste; reduces landfill use.	High energy consumption; output quality varies with feedstock.	[133]
Gasification	Mixed PE, PP, other plastics	Conversion of plastics to syngas (hydrogen and carbon monoxide) through partial oxidation at high temperatures. Syngas can be processed into chemicals or fuels.	Syngas, which can be converted to methanol, ammonia, or other chemicals	Flexible output products; can process a wide range of waste plastics.	Technically complex; requires clean feedstock to prevent syngas contamination	[134]
Chemolysis (e.g., Hydrolysis, Methanolysis)	Primarily works for other polymers, research ongoing for PE, PP	Use of solvents or chemicals to break down polymers into monomers or other chemicals.	Monomers, oligomers, or specific chemicals depending on the process	Potential for high-purity outputs; lower temperature process than pyrolysis or gasification.	Less developed for polyolefins; often requires pure and pre-sorted plastic waste.	[135]

Energy recovery of polyolefins

Energy recovery of polyolefins involves the conversion of the energy content of plastics into usable forms of energy like heat, electricity, or fuel through incineration or advanced thermal treatment methods, as summarized in Table 9.

Table 9. Energy recovery of polyolefins.

Energy Recovery Method	Description	Inputs	Outputs	Advantages	Challenges	Ref.
Incineration	Combustion of waste to generate heat, which can be used to produce steam for electricity generation or heating purposes.	Mixed plastic waste, including contaminated or non-recyclable PE and PP.	Heat, electricity, ash, emissions (CO_2, NOx, etc.).	Reduces the volume of waste; generates energy; relatively well-established technology.	Emissions require control and treatment; public opposition; and potential loss of materials that could be recycled.	[136]
Cement Kilns	Co-processing of plastic waste as a partial replacement for fossil fuels in cement production.	Non-recyclable plastics like PE and PP, are mixed with other wastes.	Heat for cement production, reduced use of fossil fuels, emissions.	Utilizes waste as a resource; reduces greenhouse gas emissions compared to traditional fuels.	Limited by cement industry capacity; emissions and ash management.	[137]
Pyrolysis for Fuel Production	Thermal decomposition of plastics in the absence of oxygen to produce liquid and gaseous fuels.	Suitable for PE, PP, and a mix of other plastics.	Pyrolysis oil (can be refined into fuels), syngas, char.	Produces fuels from waste plastics; can handle mixed plastics.	Technology is still being scaled up; energy-intensive; requires clean feedstock for high-quality output.	[138]
Gasification	Conversion of plastics into syngas (a mixture of hydrogen and carbon monoxide) through controlled partial oxidation.	Mixed plastics, including PE and PP.	Syngas (for energy or chemical synthesis), slag, emissions.	Flexible output (energy or chemical products); reduces landfill use.	Technologically complex, high capital and operational costs; requires gas clean-up systems.	[139]

Case Studies of Sustainable Practices

As the need to reduce the environmental impact of polyolefinic materials, such as polyethylene and polypropylene, increases in the packaging industry, sustainable practices have gained greater importance. Analyzing case studies of sustainable packaging practices provides essential knowledge for businesses to minimize waste, enhance recyclability, and move towards a circular economy [140, 141]. By 2025, Unilever intends to ensure that all its plastic packaging is reusable, recyclable, or biodegradable. Unilever has invested in a closed-loop recycling system for recovering and reusing polyolefinic materials. By allying with advanced recycling firms, the company successfully doubled the proportion of post-consumer recycled plastic in its packaging. The "World Without Waste" campaign by Coca-Cola exemplifies their adoption of a circular economy model. By promoting the recovery and recycling of polyolefin materials, this initiative aims to enhance packaging sustainability, with Coca-Cola leading the way through innovative designs and partnerships with local recycling facilities. The company intends to use 50% recycled content in its PET plastic bottles by 2030, thereby boosting polyolefin-based recycling. The European Union's Plastics Strategy entails regulatory measures to decrease plastic waste within the region. By designing easier-to-recycle plastic products, manufacturers impact the production of polyolefinic materials for packaging. Through ambitious targets for plastic reduction and mandatory recyclability increases, the EU demonstrates its commitment to promoting sustainable industry practices using polyolefins.

CONSUMER PERSPECTIVES AND MARKET TRENDS

Public awareness and perceptions

Public perceptions and awareness of polyolefin packaging impact consumer perspectives and market trends, as multiple research studies have demonstrated. Customers now prioritize sustainable packaging options, such as recyclable and biodegradable materials, due to heightened awareness of environmental issues. Research indicates an increasing inclination towards packaging options that reduce ecological footprints and encourage conscientious usage. In addition, the way that consumers view polyolefin packaging has changed over time, with a focus on attributes like environmental impact, recyclability, and reuse [142, 143]. Thus, producers and labels adapt to these changing consumer inclinations by using environmentally friendly materials for packaging and being open about their sustainability efforts. Based on market trends and consumer demand for more environmentally friendly polyolefin packaging options, these findings highlight the importance of public perceptions and awareness, as depicted in Figure 6 [142].

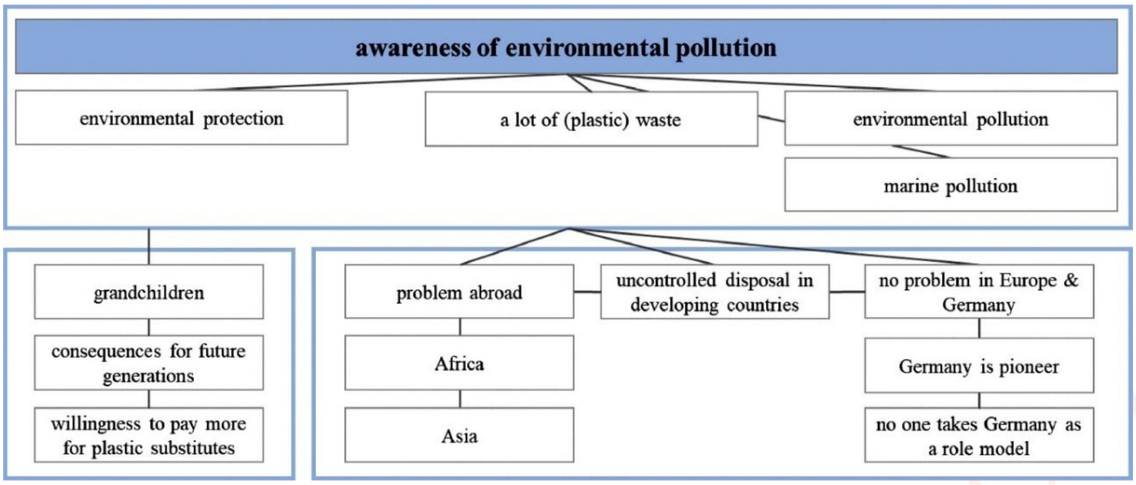

Figure 6. Consumer awareness in polyolefinic packaging. Image reproduced with permission from Ref [142].

Demand for sustainable packaging solutions

Environmental issues surrounding packaging made of polyolefins have had a big influence on market dynamics and customer behaviour. Based on recent studies, there is a growing trend for sustainable packaging alternatives, such as recyclable, compostable, and biodegradable materials, as a result of growing public awareness of plastic pollution and its negative environmental effects. Widely utilized for its affordability and sustainability, polyolefin packaging is currently being criticized for its impact on the environment and its contribution to the rise in plastic trash [144]. According to studies, consumers are now considering factors including packaging materials' post-consumer management, recyclability, and environmental impact. Manufacturers are being forced by this shifting viewpoint to alter packaging design, for example, by adding bio-based additives or creating blends of polyolefin that are more recyclable and biodegradable [145]. Furthermore, many studies have underlined how crucial it is to communicate openly about sustainability issues so that customers may make knowledgeable choices and promote ethical packaging in the polyolefin industry. In light of this, it is imperative to combine environmental performance evaluation with materials innovation to satisfy the rising demand for sustainable packaging.

Impact on Manufacturers and Brand Owners

Manufacturers and brand owners have been significantly impacted by shifting customer perceptions and market trends around polyolefin packaging. Manufacturers are being compelled to use eco-friendly practices as a result of growing public awareness of environmental issues and the need for sustainable packaging solutions [146,147]. According to recent studies, the use of recycled and biodegradable polyolefins in package formulations is becoming more popular as a way to lessen environmental effects and promote the circular economy model. Moreover, manufacturers are being encouraged to invest more in research and development (R&D) to create novel materials and environmentally friendly packaging solutions with enhanced reusability and degradability qualities by market-driven sustainability initiatives [148]. In addition to guaranteeing better environmental results, this development is crucial for fulfilling regulatory requirements in light of the global adoption of more stringent environmental regulations and Extended Producer Responsibility (EPR) frameworks [149]. Furthermore, implementing sustainable packaging techniques offers chances to lower reputational concerns related to ecologically unsound business operations and sustain a competitive market position over time. Sustainable packaging techniques are therefore becoming more and more important to producers and brand owners to meet shifting consumer, environmental, and regulatory demands.

Market value of global manufacturers

The manufacture of polyolefins is experiencing substantial economic expansion, according to a recent market analysis. For instance, the market value of China National Petroleum Corporation (CNPC) was estimated to be US$281.2 billion in 2022 and is expected to increase at a compound annual growth rate (CAGR) of 4.8% to reach US$410.4 billion by 2030. Additionally, other top producers like Arkema, ExxonMobil, LyondellBasell, and SABIC are steadily growing their production capacity and market share, demonstrating the ongoing demand for packaging materials based on polyolefins worldwide. These market trends indicate that to comply with environmental laws and public awareness, the industry must adopt recyclable and sustainable practices [150, 151].

CHALLENGES AND OPPORTUNITIES

Technological and economic barriers

The adoption of polyolefinic packaging solutions faces major challenges from both technological and economic barriers. From a technological standpoint, significant research and funding are needed to develop advanced recycling techniques and biodegradable materials. Technological innovations in recycling, like chemical or mechanical processes, require more infrastructure and knowledge than traditional methods, which raises the cost of implementation. Furthermore, because the upfront costs and ongoing expenses frequently exceed the potential cost savings, the economic viability of these solutions is still an issue [152]. Furthermore, producers face financial difficulties due to the market competitiveness of recycled or biodegradable polyolefins in comparison to conventional packaging materials. Notwithstanding these obstacles, there are ways to get around them: cooperative research projects, financial aid from the government, and consumer awareness campaigns.

Opportunities for Innovation and Development

Several research studies have emphasized how challenges in polyolefin packaging offer chances for innovation and development. To solve environmental issues, creative solutions include the creation of biodegradable polyolefins, cutting-edge recycling techniques, and unique package designs. A major advancement in packaging systems that aims to improve product safety and prolong shelf life is the integration of functional aspects, such as active and intelligent packaging [153, 154]. Active packaging is a system that interacts with the packaged product or the environment to help extend the shelf life or maintain the quality of the product, for example, adding antimicrobial agents or oxygen scavengers to polyolefin films [155]. This type of packaging is particularly useful for the food and pharmaceutical industries, where freshness and safety are of paramount importance. On the other hand, intelligent packaging refers to technologies that incorporate sensors, freshness indicators, or QR codes that can provide real-time information about the condition of the product. Incorporating such features into polyolefin materials opens up new avenues for smart supply chain management, proactive communication with consumers, and food waste reduction, as it allows consumers and retailers to make informed decisions [156]. Furthermore, improvements in coating methods and nanotechnology may strengthen the barrier qualities against moisture and oxygen, which would boost packaging efficiency. the promotion of resource sharing and knowledge exchange, collaborative efforts amongst industries, policymakers, and research institutions further propel innovation. These opportunities boost economic growth and competitiveness in the polyolefin packaging industry, in addition to supporting sustainable packaging practices.

Role of policy and regulation in shaping the future

There are opportunities and challenges associated with the role that policy and regulation will play in determining the future of polyolefin packaging. Environmental regulations that are designed to reduce plastic waste and promote sustainability present difficulties for manufacturers because they require them to use eco-friendly materials and comply with recycling targets. These rules, however, also present chances for investment in and innovation regarding sustainable practices. Eco-friendly packaging solutions are the focus of research and development efforts driven by policies that incentivize the use of recycled materials and the development of biodegradable alternatives. Furthermore, laws requiring extended producer responsibility push manufacturers to assume more responsibility for the packaging materials' end-of-life management, supporting closed-loop systems and circular economy projects. Proactive engagement with policy frameworks can result in long-term benefits, such as improved environmental performance, enhanced brand reputation, and access to emerging markets focused on sustainability, even though compliance with regulations may incur initial costs.

There are several important considerations for the production of sustainable polyolefin packaging materials [157].

- Designing for a Circular Economy (D4ACE) Guidelines: The rules primarily address flexible packaging constructed of polyolefin-based materials, such as mono-PE, mono-PP, and PE/PP blends. Polyolefins account for a significant proportion of post-consumer flexible packaging trash. The guidelines provide practical solutions based on circular economy principles, with a particular emphasis on improving recyclability. They advocate for the use of mono-PE and mono-PP constructions whenever possible, supporting designs that simplify recycling and reduce environmental impact.

- Barrier Layers and Coatings: Barrier materials and coatings are critical components of flexible packaging structures, greatly enhancing their functionality. They increase performance while reducing the amount of material required.

- Sustainable Approaches: To ensure a consistent supply of packaging materials throughout the year while minimizing environmental impact, two critical measures must be prioritized. To begin, emphasize material recycling and reuse whenever possible. Second, choose environmentally friendly materials, such as bio-based and biodegradable options. These ideas promote package sustainability while reducing environmental effects.

- Active Packaging Films: Polyolefins, such as polyethylene and polypropylene, that have been modified to incorporate organic and inorganic nanoparticles show promise for application in sustainable packaging.

- Biodegradable Plastics: Biodegradable plastics are gaining popularity as alternatives to traditional plastics, helping to reduce the environmental effects of packaging materials.

CONCLUSION

The study of polyolefinic materials in packaging reveals both attractive opportunities and substantial environmental risks. While polyolefins are versatile and cost-effective, their extensive use leads to plastic pollution and creates recycling issues. However, advances in biodegradable and bio-based alternatives hold promise for minimizing these environmental effects. Moving forward, the packaging industry must prioritize sustainability by using environmentally friendly materials and creative recycling technologies. This comprehensive analysis underlines the need to resolve environmental challenges related to polyolefinic packaging, as well as the urgent need for long-term solutions to ensure a more environmentally conscious future.

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AUTHORS' CONTRIBUTION

Anirban Bhar (Formal analysis, Writing – original draft), Akshay Kumar Dey (Data curation, Visualization, Writing – review and editing), Deepsikha Datta (Investigation, Supervision, Validation, Writing – review and editing), Oliva Roy (Methodology), Soumyadeep Routh (Resources), Arindam Mondal (Investigation, Supervision), Biswajit Kamila (Investigation, Supervision, Validation, Writing – review and editing)

CONFLICTS OF INTEREST

The authors do not have any conflicts of interest to declare.

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