Chemical Engineering Journal 515 (2025) 163633

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

Review

Advancements in the production methods and recycling of multilayer plastics with sustainable applications: A comprehensive review

Maha Awjan Alreshidi [a], Krishna Kumar Yadav [b,c,*], G. Shoba [d], Amel Gacem [e], S. Padmanabhan [f], T. Vinod Kumar [g], Ahmed M. Fallatah [h], Javed Khan Bhutto [i], Fahad M. Aldosari [j], Manawwer Alam [k], Muhammad A. Abo El-Khair [l], P. Tamizhdurai [m,*], A. Subramani [n], V.L. Mangesh [o], R. Kumaran [m]

[a] *Department of Chemistry, College of Science, University of Ha'il, Ha'il 81451, Saudi Arabia*
[b] *Department of VLSI Microelectronics, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai -602105, Tamil Nadu, India*
[c] *Environmental and Atmospheric Sciences Research Group, Scientific Research Center, Al-Ayen University, Nasiriyah, Thi-Qar 64001, Iraq*
[d] *Department of Biotechnology, Dwaraka Doss Goverdhan Doss Vaishnav College (833, Gokul Bagh, E.V.R. Periyar Road, Arumbakkam, Chennai 600 106 Tamil Nadu, India*
[e] *Department of Physics, Faculty of Sciences, University 20 Août 1955, Skikda, Algeria*
[f] *Department of Mechanical Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India*
[g] *Department of Mechanical Engineering, Vels Institute of Science, Technology & Advanced Studies (VISTAS), Chennai, India*
[h] *Department of Chemistry, College of Science, Taif University, P.O. Box 11099, 21944 Taif, Saudi Arabia*
[i] *Department of Electrical Engineering, College of Engineering, King Khalid University, Abha, Saudi Arabia*
[j] *Department of Physics, College of Science and Humanities in Al-Kharj, Prince Sattam bin Abdulaziz University, Saudi Arabia*
[k] *Department of Chemistry, College of Science, King Saud University, Riyadh 11451, Saudi Arabia*
[l] *Egyptian Petroleum Research Institute, Nasr City, Cairo 11727, Egypt*
[m] *Department of Chemistry, Dwaraka Doss Goverdhan Doss Vaishnav College (Autonomous) (Affiliated to the University of Madras, Chennai), 833, Gokul Bagh, E.V.R. Periyar Road, Arumbakkam, Chennai 600 106 Tamil Nadu, India*
[n] *Department of Bio Chemistry, Dwaraka Doss Goverdhan Doss Vaishnav College (Autonomous) Arumbakkam, Chennai 600 106 Tamil Nadu, India*
[o] *Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, Vaddeswaram, Guntur, Andhra Pradesh 522502, India*

ARTICLE INFO

Keywords:
Biobased plastics
Multilayer Plastics (MLP)
Recycling process
Environment
Pyrolysis process

ABSTRACT

In recent years, multilayer polymers (MLPs) have become increasingly popular because of their excellent barrier properties and long-lasting durability, which make them well-suited for a wide range of packaging applications. These barrier properties include the prevention of gas (oxygen, carbon dioxide, and nitrogen), moisture, aroma, and light permeation, ensuring product quality, freshness, and extended shelf life. However, their complex structures and widespread use present significant challenges for recycling, with limited practical solutions available. Mono-material MLPs offer a more sustainable and recyclable alternative compared to multi-material MLPs. Additionally, the simplicity and cost-effectiveness of layer-by-layer assembly may provide an advantage over traditional MLP manufacturing techniques. This review focuses on the production, properties, and recycling processes of multilayer films. It covers prior research on various recycling methods, including biochemical, thermochemical, mechanical, and chemical approaches. Specific chemical recycling methods, including methanolysis, aminolysis, delamination, glycolysis, hydrolysis, solvent-based techniques, and catalytic depolymerization, are extensively explored. The review also emphasizes the established pyrolysis method and investigates the potential of biological recycling methods, such as enzyme-mediated catalysis. Emerging technologies and innovative solutions, such as the use of compostable plastics, biodegradable materials, cellulose-based products, and bio-based polymers, are discussed as pathways to achieving a circular economy. The life cycle assessment (LCA) of MLP recycling is analyzed, along with its economic implications. The review emphasizes the importance of ongoing research, innovation, and industry-wide collaboration in addressing the environmental challenges

---

* Corresponding authors at: Department of VLSI Microelectronics, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai -602105, Tamil Nadu, India (K.K. Yadav).
E-mail addresses: envirokrishna@gmail.com (K.K. Yadav), p.tamizhdurai@dgvaishnavcollege.edu.in (P. Tamizhdurai).

https://doi.org/10.1016/j.cej.2025.163633
Received 6 February 2025; Received in revised form 3 May 2025; Accepted 10 May 2025

posed by multilayer plastics and fostering a sustainable future. This resource aims to guide prospective researchers in developing and implementing sustainable MLP recycling strategies.

1. Introduction

Over the past 50 years, plastic has displaced other materials and taken over as the most common substance in modern society, becoming an essential part of everyday life [1]. Over 40 % of the world's plastic production is used in the wrapping sector, making it the most significant application for plastics [2]. Coincidentally, because of their stable chemical structure, most plastics break down quite slowly in the environment. Consequently, as seen in Fig. 1, a considerable amount of plastic manufacture may be produced each year. The world produces more than 420 million metric tonnes of plastic waste annually. The world will confront a huge, possibly unsolvable problem if usage is not significantly reduced and recycling is not boosted [3].

Despite their broad range of uses, polymeric films are typically classified into two categories: wrapping and nano-wrapping, each serving specialized functions based on performance requirements [5]. Consumer packaging (found in secondary and tertiary packaging) and commercial goods (found in primary packaging) are two different categories [6]. The main objective of commercial wrapping is to protect the products. Combining many primary components for simple and safe transit is the goal of secondary and tertiary wrapping [7]. Flexible films are classified into monolayer and multilayer types depending on their structure. Monolayer films, primarily used in tertiary and secondary packaging due to their cost-effectiveness and simplicity, have limited applications in construction and agriculture, where more specialized materials are required. On the other hand, multi-layered films have many covers composed of non-polymeric or polymerised materials, including foil-like aluminium or paper-based wrappers. Food packaging application for multilayer films, which currently make up 17 % of the world's flexible film production [8]. Low-density polyethene [9] and high-density polyethene [10] are the most often used polymers for consumer packaging, followed by polyethylene terephthalate [11] and polypropylene [12]. The material that is widely utilized in agriculture and other non-consumer products for packaging is linear low-density polyethene [13]. The representation of the quantitative and statistical data on polymer usage was depicted in Table 1.

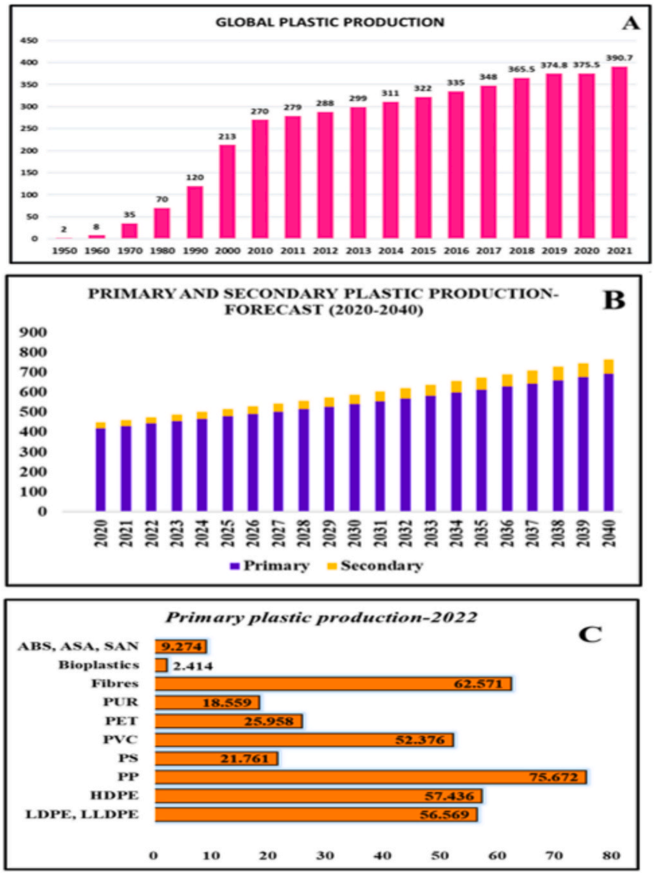

Fig. 1. A) Global plastic production overview (1950——2040) in Million metric tons. B) Global primary and secondary plastic production forecast in million metric tons (2020—2040) C) Global primary plastic production by polymer type, measured in million tonnes in 2022 [4].

Recent research has highlighted concerns about the impact of incinerating plastic packaging waste on greenhouse gas (GHG) emissions. To mitigate these environmental effects, alternative conversion technologies such as pyrolysis, gasification, fermentation, and hydrothermal carbonization have been explored. The pathways for these conversion processes and their potential to recover valuable resources from plastic aste are also depicted in Fig. 2 and also presents an overview of these conversion processes, highlighting their role in promoting circular economy principles and sustainable waste management. Multilayer plastic recycling has gained popularity at the same time, and numerous businesses and organisations have created new tools and methods to meet this need. Compatible compounds [14], which are compounds that aid in bonding the various polymers in multilayer plastic and facilitate recycling, are one example of this type of technology. Compatibilizers have been demonstrated to enhance recycled plastic's quality, increasing its suitability for application in new goods. The development of closed-loop systems [15], which enable continuous plastic recycling and reduce the demand for virgin plastic production, is an emerging trend in multilayer plastic recycling. These systems support a circular economy by collecting waste plastic, processing it into innovative products, and subsequently recycling those products for repeated use, fostering sustainability [16].

Although multimaterial multilayer plastics offer versatility and improved performance, recycling them is difficult since individual polymer layers must be separated and treated using specialised procedures. Multimaterial multilayer films, typically composed of two to nine layers [17], are engineered to meet a variety of performance requirements, including food compatibility, mechanical strength, heat sealability, and gas, aroma, and moisture barriers [18]. These combined properties make them ideal for packaging applications, particularly in

Table 1
Representation of the quantitative and statistical data on polymer usage.

Polymer	Global Market Share	Annual Production (Metric Tons)	Key Applications
Low-Density Polyethylene (LDPE)	~10 %	>5 million	Flexible packaging (plastic bags, wraps)
High-Density Polyethylene (HDPE)	~30 %	>50 million	Rigid containers, bottles, industrial packaging
Polyethylene Terephthalate (PET)	~>20 %	>30 million	Beverage bottles, food containers
Polypropylene (PP)	~25 %	>70 million	Rigid containers, packaging films, non-woven fabrics
Linear Low-Density Polyethylene (LLDPE)	~15 %	>6 million	Agricultural applications, flexible packaging

the food industry, where they contribute to enhanced shelf life and improved product protection. However, the complexity of these films, due to their multiple layers, presents significant challenges for recyclability. Traditional mechanical recycling methods are often ineffective for multilayer plastics, limiting their potential for reuse. To overcome these challenges, alternative recycling methods have been proposed, such as chemical recycling via pyrolysis [19] and solvent-based dissolution processes followed by mechanical recycling [20]. These innovative approaches hold promise for improving the recyclability of multimaterial multilayer plastics while preserving their desirable performance attributes.

Because multilayer plastics have an impact on the environment at the end of their lifecycle, it is imperative that functionality and sustainability be balanced during development and use. Multilayer plastic recycling is essential to reducing the environmental effects of plastic waste. While challenges persist, innovative strategies and technologies are emerging to enhance the recycling process. A concise overview of multilayer flexible packaging, including its unique properties, role in sustainability, and challenges with conventional recycling methods, helps.

facilitate discussions on the future development of this packaging type. It will take research to combine barrier packaging's recyclability with environmental sustainability in general. Multilayer plastic recycling presents a promising approach to mitigating the environmental challenges associated with plastic waste. However, the extent of its effectiveness depends on overcoming current technological and economic barriers. This review explores whether advancements in recycling technologies and material innovations can provide clear environmental benefits. It addresses critical questions, including the specific environmental impacts of multilayer plastics, the effectiveness and limitations of existing recycling technologies in addressing these impacts, and the material combinations and recycling methods that show the greatest potential for scalability and sustainability.

Recycling multilayer plastics faces significant challenges due to the diverse materials used in each layer, variations in polymer processing properties, and the absence of efficient detection and collection systems. Although recycling through mechanical method can recover waste and provide feedstock for production of new plastic, it cannot produce materials that retain their original composition or strength, limiting its effectiveness [21]. The removal of used ink, adhesives, coatings, and labels is a complex task. The blend of various materials, namely polymers, paper, metals, and various coatings, makes recycling multilayer plastic packaging particularly challenging. However, chemical recycling methods such as delamination, hydrolysis, and glycolysis, offer efficient solutions for breaking down multilayer plastics into their individual components for reuse. Although new chemical recycling systems like solvent-targeted recovery and precipitation (STRAP) show promise, they need to be further studied and scaled up. In order to increase multilayer flexible packaging's recyclability within the current infrastructure for collection, sorting, and recycling, efforts are being undertaken to redesign it [22].

The entire life cycle of multilayer plastics (MLPs), from production to

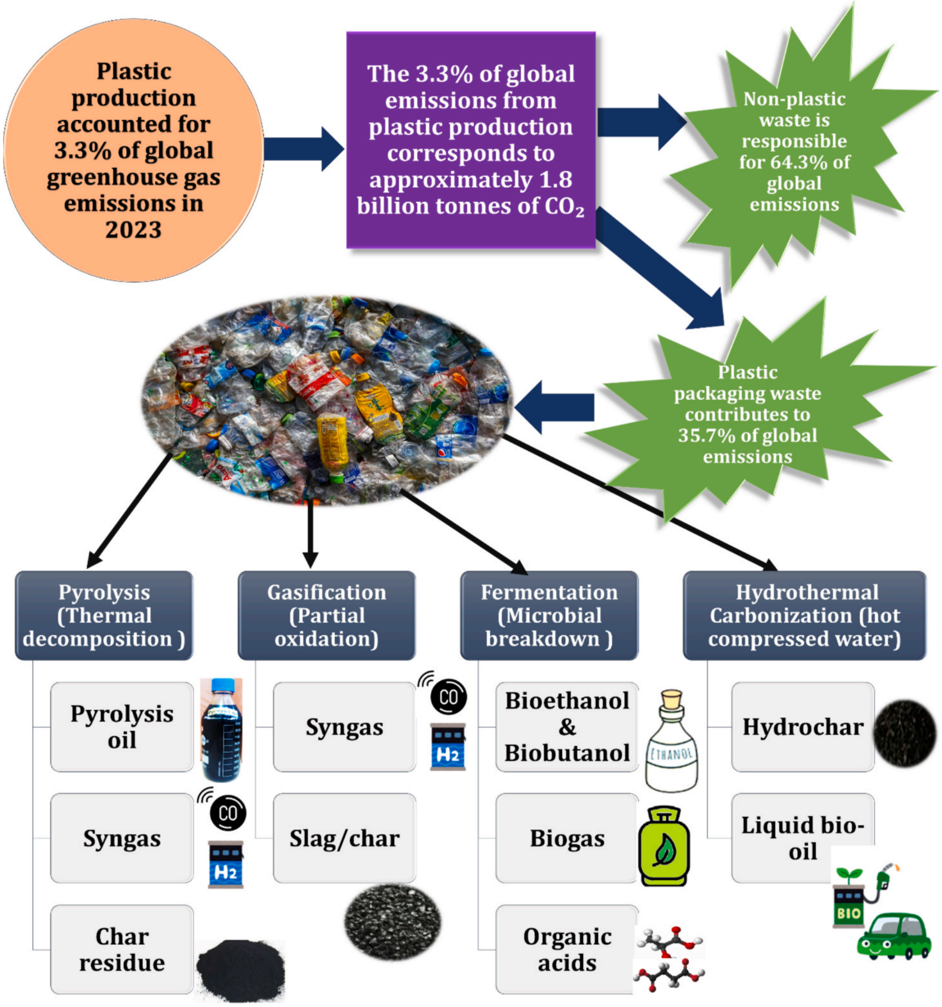

Fig. 2. Outlook of greenhouse gas emissions with plastic packing waste production.

end-of-life, warrants a comprehensive analysis to understand its environmental implications and identify sustainable solutions. Recycling MLPs has been proposed as a potential long-term strategy for addressing the challenges posed by plastic waste. However, the effectiveness of this approach depends on overcoming significant barriers at each stage of the recycling process, which typically includes collection, sorting, cleaning, shredding, separating layers, and recycling the constituent materials. This review seeks to critically examine these stages, exploring the efficiency of current methods for collecting and sorting MLPs, the technical and economic challenges in separating layers and recycling materials, and the potential for advancements in recycling technologies to provide scalable and sustainable solutions. By addressing these aspects, the review aims to evaluate the viability of MLP recycling as a sustainable waste management strategy. However, the recycling of multilayer plastics faces several challenges, such as inadequate infrastructure, high costs, and complex compositions. Despite these challenges, ongoing efforts aim to create environmentally sustainable solutions to tackle these issues. Recent advancements in recycling technologies and the development of sustainable materials have shown promise in addressing the challenges posed by plastic waste. Materials derived from biomass, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA), provide renewable alternatives to traditional plastics, offering improved biodegradability and reduced dependence on fossil fuels. Innovations in multilayer plastic recycling, such as advanced depolymerization methods, solvent-based extraction, and enzymatic recycling, have also emerged as potential solutions for recovering valuable materials from complex plastic structures. While these advancements represent significant progress, they often serve as temporary fixes for achieving recycling goals. The scalability, cost-effectiveness, and environmental impacts of these technologies need further evaluation to ensure they provide long-term and sustainable solutions.

The global shift from fossil-based plastics to bioplastics marks a significant step toward sustainability, driven by environmental concerns, policy regulations, and advancements in material science. Despite their potential, bioplastics face several challenges, including high production costs, competition for feedstock with food production, and inefficiencies in end-of-life (EOL) management [23,24]. While certain bioplastics offer biodegradability, existing recycling infrastructure is often ill-equipped to handle them efficiently, leading to uncertainties in waste management [25]. However, integrating bioplastics into a circular economy necessitates advanced recycling technologies such as chemical depolymerization and enzymatic degradation, alongside policy-driven interventions like extended producer responsibility (EPR) programs and government incentives [26]. Technological advancements have improved the material properties of bioplastics, with innovations in polymer chemistry enhancing durability and functionality, making them viable alternatives to petroleum-based plastics [27]. The adoption of bio-based solvents, such as Cymene, and biotechnological approaches like microbial synthesis of polyhydroxyalkanoates (PHAs) and polylactic acid (PLA), further strengthen the case for bioplastics by improving compostability and lifecycle performance [23]. Life cycle assessments indicate that bioplastics can significantly reduce carbon footprints, particularly when powered by renewable energy sources [23]. Nevertheless, addressing scalability concerns requires the standardization of bioplastic identification, revisions in life cycle assessment guidelines, and clear regulatory frameworks to support large-scale adoption [28]. By overcoming these barriers through industrial collaboration, technological innovation, and strategic policy implementation, bioplastics can transition from niche applications to widespread use, playing a crucial role in establishing a truly sustainable plastic economy.

2. Fabrication of materials for multilayer plastics: methods and insights

The composite or multilayer materials with cutting-edge technology are used to create multi-layered packaging, which offers strength, storage stability, and food barrier properties [29]. Some of the most widely used polymers in the packaging industry include polyamide (Nylon, PA), polypropylene (PP), ionomers [(ethylene-co-acrylic acid (EAA), ethylene-co-methacrylic acid (EMAA)], ethylene–vinyl alcohol (EVOH), polyethylene (PE), and ethylene vinyl acetate (EVA). Multilayered wrapping often incorporates a variety of materials, including paper, polymers, and metals [30]. Table 2 provides a list of some of the most widely available polymers currently on the market. Polyethylene is the most commonly used and cost-effective packaging film. Cereal bag sheets made from LLDPE, LDPE, and HDPE are often combined with an odor barrier, while polypropylene (PP) sheets are typically used for cereal bags that require enhanced mechanical or thermal resistance [31].

The Limiting Oxygen Index (LOI) is a critical parameter in assessing the flammability of polymers, indicating the minimum concentration of oxygen required to sustain combustion. Higher LOI values correspond to greater flame resistance. For instance, Polyvinyl Chloride (PVC) exhibits an LOI of 26–28 %, signifying superior flame retardancy compared to Polypropylene (PP) and Low-Density Polyethylene (LDPE), which have LOI values of 17–18 % and 16–17 % respectively.

Chemical resistance varies among polymers, with resistance typically measured across different pH levels. Polytetrafluoroethylene (PTFE) demonstrates exceptional chemical resistance, maintaining stability across a broad pH range from 1 to 14. In contrast, Polystyrene (PS) is more susceptible to chemical attack, particularly in environments with pH levels outside the 3–9 range.

Temperature versatility is another crucial property, defining the operational temperature range of polymers. PTFE stands out with a remarkable service range from $-200\ ^\circ$C to $260\ ^\circ$C, making it suitable for extreme temperature applications. Conversely, Polyvinyl Chloride (PVC) is limited to a narrower range of $-10\ ^\circ$C to $60\ ^\circ$C, restricting its use in more temperature-variant environments [32]. Understanding these properties is essential for selecting appropriate materials in various applications, ensuring safety, durability, and performance.

Table 3 illustrates typical laminated multilayer plastic film constructions. Ethylene copolymers, such as EMAA, EVA, and EAA, are key materials in this category. While the copolymerization of polar monomers enhances adhesion, stiffness, and clarity, it lowers the melting temperature and crystallization, which can reduce durability. These copolymers serve as thermally sealable interfaces or tie layers when combined with co-extruded olefins and polar monomers namely PET and PA.

The percentages reported in the table represent the weight percentages of each constituent material within the respective multilayer film structures. This means that each percentage indicates the proportion by weight of a specific material relative to the total weight of the entire multilayer film. For instance, in the structure labeled “LLDPE / HMW-HDPE / LLDPE,” the composition is detailed as LLDPE (40 %) / HMW-HDPE (20 %) / LLDPE (40 %), signifying that LLDPE constitutes 40 % of the total weight, HMW-HDPE accounts for 20 %, and the remaining 40 % is again LLDPE. This method of specifying compositions by weight percentage is a standard practice in the field of polymer science and engineering, as it provides a clear understanding of the material distribution within composite structures. For example, in the patent “Multilayer film structure” (WO2008138133A1), the compositions of various layers within a multilayer film are described in terms of weight percentages, facilitating precise formulation and reproducibility of the film’s properties [32].

2.1. Exploring multimaterial and multilayer plastic systems

In combination with inorganic films such as SiO_2 or Al, polymeric coatings can be used in flexible multilayer packaging and act as a defensive laminate. Typically, it consists of two to twenty-four layers [40]. Every layer contributes significantly to the design (Table 4). The

Table 2
The large range of polymers its Abbreviation, properties and Multitude of Plastics Applications.

Polymer	Key Constituents	Key Properties	Durability (Years)	Flame Resistance (LOI, Oxygen Index)	Chemical Resistance (pH range)	Versatility (Temperature range °C)	Low Cost (Cost/kg)	Applications
Polypropylene (PP)	Propylene monomer	Lightweight, chemical resistant	5–10	17–18 % (Oxygen Index)	pH 2–12	−20 to 100	$1.10-$1.60	Packaging, automotive parts, textiles
Low-Density Polyethylene (LDPE)	Ethylene monomer	Flexible, moisture-resistant	2–5	16–17 % (Oxygen Index)	pH 2–12	−50 to 80	$1.00-$1.50	Plastic bags, films, cable insulation
High-Density Polyethylene (HDPE)	Ethylene monomer	Rigid, impact-resistant	10–15	18–20 % (Oxygen Index)	pH 3–12	−50 to 120	$1.00-$1.60	Bottles, pipes, toys, fuel tanks
Polyvinyl Chloride (PVC)	Vinyl chloride monomer	Durable, flame-retardant	20–30	26–28 % (Oxygen Index)	pH 1–14	−10 to 60	$1.30-$2.00	Pipes, flooring, medical tubing
Polystyrene (PS)	Styrene monomer	Lightweight, insulating	1–5	18–19 % (Oxygen Index)	pH 3–9	−40 to 80	$1.00-$1.60	Packaging, insulation, disposable cups
Polyurethane (PU)	Polyols and isocyanates	Strong, transparent, recyclable	5–20	18–20 % (Oxygen Index)	pH 3–9	−40 to 120	$2.00-$5.00	Foams, coatings, mattresses, footwear
Acrylonitrile Butadiene Styrene (ABS)	Acrylonitrile, butadiene, styrene	Durable, abrasion-resistant	10–20	18–20 % (Oxygen Index)	pH 4–9	−20 to 100	$2.00-$3.00	Automotive parts, electronics, toys
Polybutylene Terephthalate (PBT)	Butylene terephthalate monomers	Strong, impact-resistant	15–25	20–22 % (Oxygen Index)	pH 3–9	−40 to 150	$3.00-$4.50	Electrical components, automotive parts
Polycarbonate (PC)	Bisphenol A and carbonyl chloride	Rigid, low friction	20–30	22–25 % (Oxygen Index)	pH 4–9	−40 to 120	$3.50-$5.00	Safety glasses, electronics, CDs
Polymethyl Methacrylate (PMMA)	Methyl methacrylate monomer	Transparent, impact-resistant	10–20	18–20 % (Oxygen Index)	pH 4–9	−40 to 85	$2.50-$3.50	Windows, lenses, signage
Polytetrafluoroethylene (PTFE)	Tetrafluoroethylene monomer	UV-resistant, weatherproof	20–50	30–32 % (Oxygen Index)	pH 1–14	−200 to 260	$10.00-$15.00	Non-stick cookware, seals, medical devices
Polyethylene Terephthalate (PET)	Ethylene glycol and terephthalic acid	Non-stick, heat-resistant	10–25	18–20 % (Oxygen Index)	pH 4–9	−40 to 120	$1.20-$2.00	Bottles, food packaging, textiles

sealant layer should establish a strong interaction barrier and stringent migration constraints because it comes into close contact with the wrapped objects. One way to do this is by using an inner layer made of polyolefin. A delicate barrier layer, namely aluminium film or TiO_2-filled acrylic surface, can also help maintain the ideal freshness of food [41]. To efficiently process packaged items, the internal film and, in some cases, the outer layer play a crucial role in sealing materials, ensuring structural integrity and product protection.

In print protection, it is common practice to reverse print the uppermost surface or all of the composite's layers [44]. The multiple levels of multi-layered packaging are shown in Fig. 3.

Four-layer multilayered plastics combine different polymers to enhance specific properties like barrier resistance, mechanical strength, and protection against environmental factors. Common layers include outer protective layers (e.g., LDPE, HDPE), middle barrier layers (e.g., EVOH, PA), and tie layers that bond the materials together was shown in Fig. 4. These films offer advantages such as improved performance, cost-effectiveness, and extended shelf life, particularly in food and medical packaging. However, challenges like complex manufacturing, higher costs, and recycling difficulties persist. Recent innovations focus on developing sustainable materials and advanced recycling technologies, with future trends likely including biodegradable films and smart packaging solutions [45]. In cases where high demands need to be met, various materials are often combined, even though the thickness, number, and arrangement of the different layers may vary. In multilayered food wrapping, the overall wrapping thickness ranges from 10 to 250 μm.

2.2. Key components in mono-material multilayer plastic structures

The packaging made of many layers of the same plastic substance is known as monomaterial multilayer plastic. This type of packaging is becoming more popular because it is easier to recycle than traditional multilayer plastics, which are made of different plastics that are challenging to separate during recycling. One type of monomaterial multilayer plastic is the PE/PE laminated sheet. PE/PE multilayer film is produced by extruding two layers of polyethylene [46]. Because it offers a high barrier to moisture, PE/PE multilayer film is effective in preserving the freshness and quality of products. However, its oxygen barrier properties are limited [47]. This makes it a more environmentally friendly and sustainable option than conventional multilayer plastics. Polylactic Acid (PLA), a biodegradable polymer derived from renewable resources such as corn starch or sugarcane, is used in monomaterial multilayer films. PLA/PLA films offer an environmentally friendly alternative to conventional plastics due to their compostability under industrial conditions. As a result, they are increasingly used in applications where sustainability is a priority, such as in the packaging of fresh produce, takeaway containers, and certain food items. PLA's ability to break down into natural components in composting facilities makes it a promising material for reducing plastic waste and promoting a circular economy [48]. Some monomaterial films, especially PE/PE and PP/PP, may not offer the same level of barrier performance as traditional multilayer films. For example, PE/PE films might not provide optimal protection against oxygen, moisture, or light, which could affect the shelf life of packaged products, especially perishable food items. While PLA/PLA films offer biodegradability, they may not provide the

Table 3
Comprehensive overview of multilayer plastic film structures: composition, properties, and uses.

Structure Design	**Composition (Approximate Ratio)**	**Key Properties**	**Applications**	**References**
LLDPE / HMW-HDPE / LLDPE	LLDPE (40 %) / HMW-HDPE (20 %) / LLDPE (40 %)	High tensile strength, Flexibility, Durability, Impact resistance, Chemical resistance, Moisture resistance, Low friction	Heavy-duty bags,Stretch films, Agricultural films, Industrial liners	[33,34]
HDPE / LLDPE / HDPE / EVA	HDPE (30 %) / LLDPE (30 %) / HDPE (20 %) / EVA (20 %)	Rigidity from HDPE, Flexibility from LLDPE and EVA, Impact resistance (EVA) ,Chemical and moisture resistance, Heat resistance	Medical pouches, Protective covers,Shrink films, Sterilizable medical products	[33–35]
Paper / LDPE / Al / LDPE	Paper (40 %) / LDPE (20 %) / Aluminum (10 %) / LDPE (30 %)	Stiffness (paper), Printability (paper) ,Light and oxygen barrier (aluminum) ,Moisture resistance, Flexibility (LDPE)	Aseptic cartons,Food packaging	[34,36]
PET / Tie / LDPE / Al / LDPE	PET (25 %) / Tie (10 %) / LDPE (25 %) / Al (15 %) / LDPE (25 %)	Strength and clarity (PET), Moisture barrier (aluminum), Flexibility and sealing (LDPE) ,Improved strength and protection	Retort pouches, Coffee packaging, Snack packaging, Ready to eat meals	[34,36,37]
LLDPE / Tie / EVOH / Tie / LLDPE	LLDPE (40 %) / Tie (10 %) / EVOH (10 %) / Tie (10 %) / LLDPE (30 %)	Excellent oxygen barrier (EVOH), Flexibility and sealing (LLDPE) ,High barrier for food freshness preservation, Chemical and moisture resistance	Vacuum sealed products, Processed food packaging	[34,38]
LLDPE / Tie / PA / Tie / LLDPE	LLDPE (35 %) / Tie (10 %) / PA (15 %) / Tie (10 %) / LLDPE (30 %)	Puncture resistance (PA), Flexibility and sealing (LLDPE), Chemical resistance (PA) ,Durability, Good mechanical strength	Frozen food films, Vacuum pouches,Meat packaging, Durable food packaging	[34,39]

same level of protection as multilayer films incorporating specialized barriers like ethylene vinyl alcohol (EVOH) or aluminum.

2.3. Additives in multilayer plastics: enhancing performance and properties

Basic ingredients called additives are added to plastic compositions to improve their usefulness and stability. These additives play a crucial role in improving the properties of multilayer plastics. Table 5 highlights some of the most commonly used additives in these materials. Sterile hindered phenols like butylated hydroxytoluene (BHT) and phosphites like trisnonylphenyl-phosphite (TNPP) are the most frequently utilized antioxidants in a variety of applications [49]. Calcium, cobalt, magnesium, and zinc stearate can also be used to produce stabilising and chemical processing effects. Polymer additives are classified into three categories by G. Wypych (2021): slide agents, release agents, and anti-blocking agents [50].

Wakabayashi et al. (2009) [58] explored slip agents in polypropylene films, highlighting the use of compounds such as erucamide and behenic acid to improve slip properties. Fatty acid amides, commonly used as slip and anti-blocking agents, offer distinct advantages over inorganic additives. Unlike fine inorganic particles, which can be challenging to incorporate into dosing systems, fatty acid amides provide smoother processing and do not compromise the transparency and gloss of films. In contrast, Espinosa et al. (2017) [59] investigated the use of talc, an inorganic anti-blocking agent, at concentrations of up to 5 % in polymer formulations. Talc was found to be a cost-effective additive with low moisture absorption; however, it can increase haze and reduce the clarity of films. Additionally, polyolefin-based resins modified with anhydride compounds are utilized to enhance interlayer adhesion in multilayer polymer structures, allowing for improved performance in applications requiring durable multilayer films. This information provides insight into the diversity of polymer additives and their roles in enhancing specific material properties, balancing cost, aesthetics, and functionality.

2.4. Optimized multilayer design: balancing barrier performance and sustainability

The selection of materials for multilayer plastic design must balance functional performance, recyclability, and sustainability to align with circular economy principles. Key parameters include mechanical integrity, interfacial adhesion, permeability control, and environmental impact reduction. The integration of recycled plastics such as polypropylene (PP), polyethylene (PE), and polyethylene terephthalate (PET) enhances sustainability while maintaining structural integrity [23]. However, achieving strong interfacial adhesion between polymer layers is crucial, as poor compatibility often limits recyclability. Compatibilizers like poly(ethylene-co-methacrylic acid) (EMA) significantly improve adhesion between incompatible polymers, enhancing mechanical properties and enabling upcycling into high-performance applications [27].

In addition to mechanical properties, optimizing permeability is essential for applications requiring selective barrier functions. Advanced microporous layer designs, such as superhydrophobic membranes, provide high organic solvent flux (14,000 $Lm^{-2}h^{-1}$) and 96 % water rejection, ensuring efficiency in demanding industrial uses [24]. Mechanical integrity parameters, including tensile strength (13–28 MPa) and strain (20–27 %), play a vital role in ensuring the reusability of multilayer materials in various applications. Furthermore, solvent-based delamination technologies, such as Switchable Hydrophilicity Solvents (SHS), enable efficient separation of multilayer components with > 99 % separation efficiency, preserving polymer integrity and facilitating recycling [25].

Sustainability considerations also include the incorporation of bio-based or plant-derived solvents, such as Cymene, which reduce

Table 4
Overview of multilayer packaging: functions, materials, and key properties (Wang et al., 2018; Bamps et al., 2023).

Layer	Common Materials Used	Key Properties	Functions	References
Seal Layer (Heat Sealability)	PET, OPET, PA, OPA, PP, OPP, Ionomers, EVA, LDPE, LLDPE	Heat sealability, flexibility,good adhesion,chemical resistance	Ensures strong seals, hermetic seal	[42,43]
Tie Layers (Combines Incompatible Materials)	Acid/anhydride grafted polyolefins, Polyurethanes	Adhesion, material compatibility, bonding between dissimilar polymers	Bonds incompatible materials,multilayer films	[43]
Light Barrier	Aluminum, TiO_2 filled polymers	UV-blocking, opacity, light barrier,prevents product degradation from light	Protects against UV/visible light degradation	[43]
Oxygen Barrier	EVOH, PA, PET, PVDC, BOPA, OPET, SiOx, Al_2O_3 coatings, Polyesters	High oxygen resistance,low permeability to oxygen,freshness preservation	Prevents oxygen ingress, preserves shelf life	[42]
Moisture Barrier	LDPE, LLDPE, HDPE, OPP, EVA, PVDC, Ionomers	Moisture resistance,barrier to water vapor	Prevents moisture,maintains freshness	[42]
Structural Layer (Toughness, Puncture Resistance, Stiffness, Mechanical Stability)	PE, PET, HDPE, PP, LDPE, PS, OPP, OPET, Paper	Toughness, puncture resistance,mechanical stability, rigidity	Puncture resistance, structural integrity	[42]

* Abbreviations: BOPA (biaxially oriented polyamide), EVA (polyethylene vinyl acetate), EVOH (ethylene vinyl alcohol), OPA (oriented polyamide), OPET (oriented polyethylene terephthalate), OPP (oriented polypropene), PVDC (polyvinylidene chloride), PVOH (polyvinyl alcohol), PE (polyethene), LD (low density), LLD (linear low density), HD (high density).

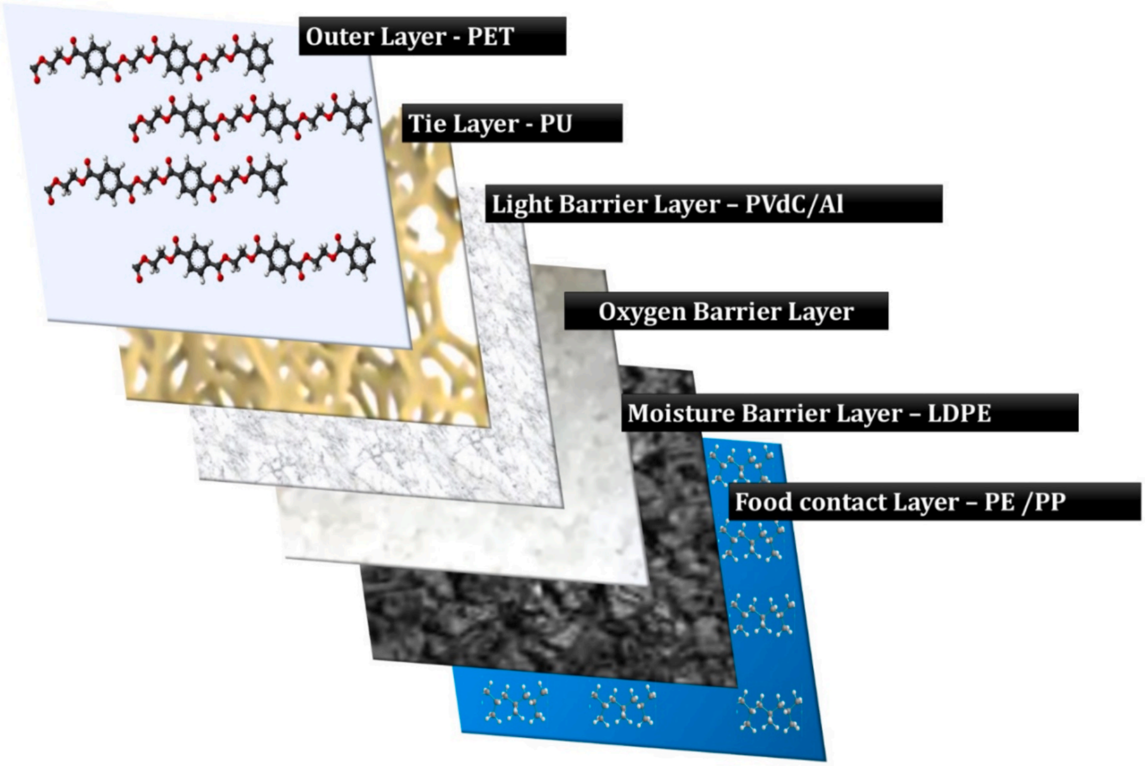

Fig. 3. Various Layer Composition of Multilayer Plastics.

reliance on petroleum-based chemicals and improve the environmental footprint of processing techniques [24]. Chemical recycling technologies, including depolymerization and thermochemical pathways, offer further potential for recovering valuable monomers and extending material life cycles [23]. The integration of these strategies in multilayer designs ensures not only superior barrier performance but also alignment with circular economy goals, promoting reduced waste generation, enhanced recyclability, and lower carbon emissions.

3. Techniques for manufacturing multilayer plastics

The different nonpolymeric and polymeric substances have been included into multiple layer wrapping systems using a variety of techniques. The most common methods for preparing multilayer films are stretch blow mounding, coinjection with lamination, coextrusion, and coating, as illustrated in Fig. 5. In order for each layer to function as efficiently as possible and achieve predetermined goals, creating multilayer packages necessitates meticulously considering the selection of preparation technique selection and variable process control. These are chosen based on polymer properties, namely its adhesiveness, interactions with other polymers, compatibility with the remaining layers, and manufacturing capacity. Table 6 illustrates the possible uses of multilayer packaging with various methods.

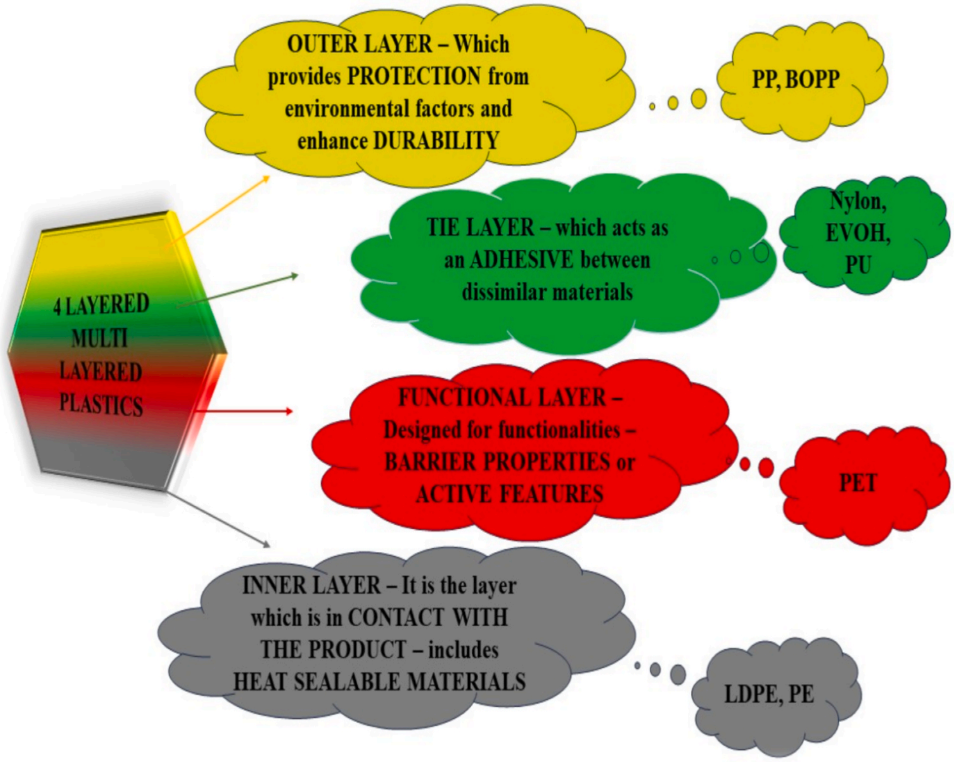

Fig. 4. Various layers of multilayer plastic film.

Table 5
The role of polymer additives: properties and their use in various applications.

Polymer Additives	Properties	Applications	Examples	References
Fillers and Mineral Reinforcements	Increases stiffness, surface hardness,reduces shrinkage, improves dimensional stability	Automotive parts, construction materials,packaging, appliances,cost reduction	Calcium Carbonate,Mica,Talc	[51]
Colourants	Adds color,enhances UV protection, improves opacity	Packaging, textiles, electronicstoys, bottles, cables	Titanium Dioxide (white pigment),Carbon Black,Liquid Colours	[52]
Heat Resistance	Delays thermal oxidation,increases durability	Electrical insulation, automotive parts,heat-exposed automotive parts,appliances	Antioxidants (e.g., Irganox),Bisphenol A (BPA)	[53]
UV Resistance	Protects from UV degradation,extends outdoor lifespan	Outdoor furniture, roofing,agricultural films,automotive components	Benzophenones,Benzotriazoles, Oxanilides	[54]
Flame Retardants	Reduces flammability,Slow ignition,meets safety regulations	Electronics, automotive interiors, textiles,construction materials,furniture.	Polybrominated Diphenyl Ethers (PBDEs), BPA	[55]
Plasticizers	Increases flexibility,softness, stretchability,reduces brittleness	Cables, flooring, medical devices, toys,packaging films	Phthalates x(e.g., DEHP, DINP),Adipates, Citrates	[56]
Cross Linking and Coupling Agents	Improves bonding,enhances mechanical and chemical properties	Rubber products,adhesives, composites, high-performance plastics	Styrene,Zinc Oxide, Peroxides	[57]

3.1. Coextrusion

Coextrusion is a widely used technique for producing multilayer films, where multiple polymer materials are heated beyond their transition temperature of glass and then extruded simultaneously through a specifically designed nozzle to form distinct layers [70]. The coextrusion process is divided into four fundamental stages: feeding, melting, stream confluence, and coextrusion. Coextrusion can be categorized into two types according on the way the diverse streams of polymers are mixed during the die and feed block step of the film-forming process. During the coextrusion process, separate extruders feed melt streams of different materials into the system independently. These materials are heated to their respective melting points and then mixed at the die exit. In feed block coextrusion, multiple materials are blended together before passing through the die. The process starts by feeding the individual melt streams of the chosen materials into a feed block, where they are combined in a controlled manner to form a multi-layered structure. This multi-layered stream is then passed through the die, which is typically hollow, to shape the material into the desired film or sheet. The feed block's design allows for precise control over the layer distribution, ensuring that each material maintains its integrity throughout the extrusion process. This method enables the production of films with multiple layers that have distinct properties, such as barrier resistance, strength, or flexibility, all within a single, continuous extrusion cycle.

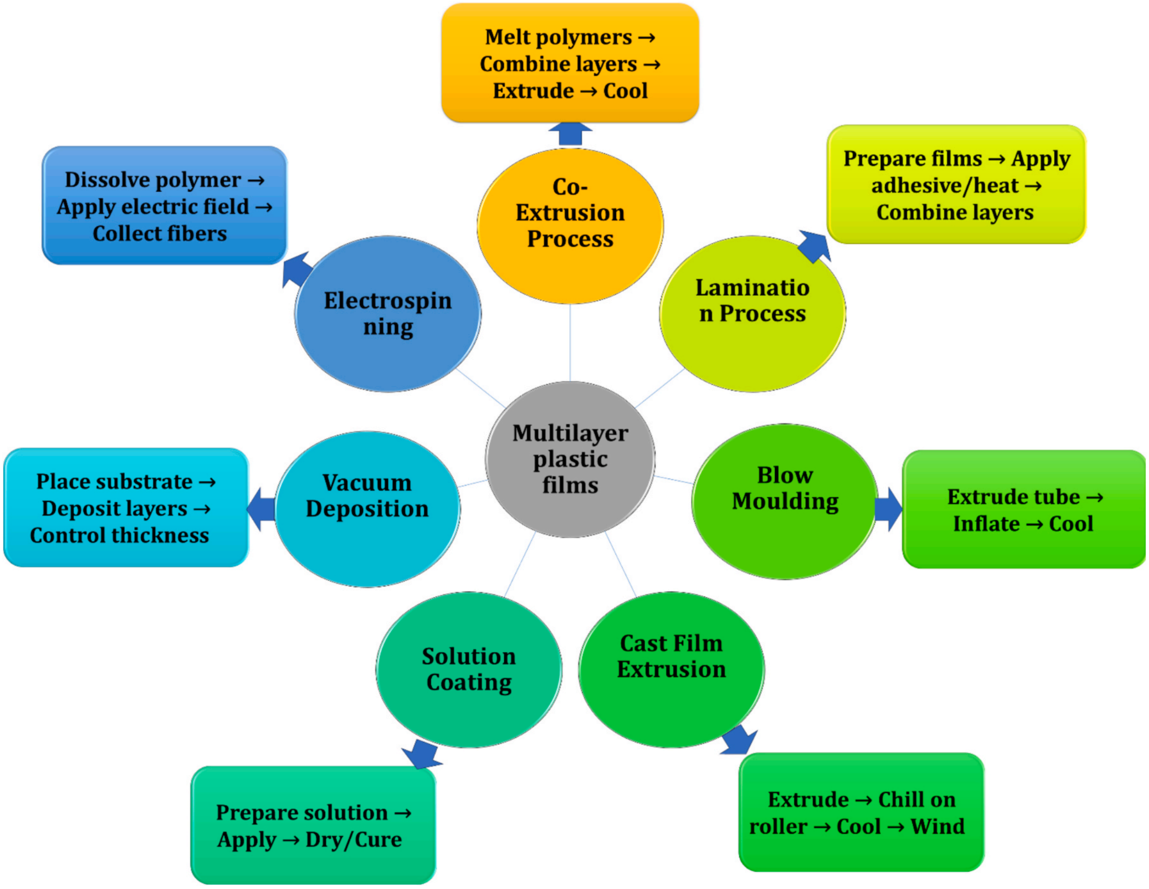

Fig. 5. Various preparation techniques of multilayer plastic films.

Table 6
Film preparation methods: extrusion coating, coating, electrospinning, and LBL assembly [46] (Source: Anukiruthika, T., et al.).

Film Preparation Method	Multilayer Packaging Composition	Method for Multilayer Preparation	Function	Application	References
Extrusion Coating	CNF-Coated Polyethylene	Coating/Surface modification of polyethylene with cellulose nanofibrils (CNF)	Modified Atmospheric Packaging	Enhanced oxygen barrier properties	[60]
	PLA/Nanoclay Multilayer (Blown Film Co-extrusion)	Blown film co-extrusion, blending PLA with nanoclay for enhanced barrier properties	Multilayer Films,high-performance, biodegradability	Enhanced oxygen barrier propertiesImproved tensile, seal strength	[61]
	PE-PA Nanocomposite (Coextrusion)	Coextrusion, combining Polyethylene (PE) and Polyamide (PA) with nanofillers	Barrier properties	Mechanical properties,oxygen barrier	[62]
Coating	PET-LDPE Multilayer for Fried Potatoes	Coextrusion or lamination, combining PET and LDPE for packaging fried foods	Antioxidant property	Lipid oxidation reduction (sage, bay extracts)	[63]
	PET/PE/EVOH/PE for MAP Foal Steaks	Coextrusion or lamination, incorporating EVOH for Modified Atmosphere Packaging (MAP)	Antioxidant property, Color Stability	Oregano and green tea essential oils – oxidative stability	[64]
Electrospinning	Fiber-Based Paper/ PVA/PHB	Blending/Co-extrusion of Paper, Polyvinyl Alcohol (PVA), and Polyhydroxybutyrate (PHB) for sustainable packaging	Moisture,aroma barrier property	Improved moisture,limonene barrier (paper)	[65]
	PE Multilayer (Spraying) for Meat	Spraying process, applying multiple layers of PE for meat packaging with moisture and oxygen barriers	Antimicrobial activity, Nanocoating	Carvacrol-loaded films reducing pathogens,bacterial count	[66]
	Chitosan-Based Multilayer	Coating/Layering of chitosan onto various substrates to enhance antimicrobial properties	Improve moisture barrier property,Antibacterial Films	PET nanocoating for reduced oxygen transmission	[67]
LBL Assembly	MTAC-rGO/EVOH Multilayer	Coextrusion or surface functionalization, combining MTAC-functionalized reduced graphene oxide (rGO) with EVOH for enhanced barrier properties	Antimicrobial activity, moisture,oxygen barrier properties	Antibacterial activity (S. aureus),moisture,oxygen barrier	[68]
	PLA-Starch (Blending/ Co-grinding)	Blending or co-grinding PLA with starch for biodegradabl	Water vapor,gas barrier properties	Mechanical resistance, moisture,gas barrier properties	[69]

3.2. Optimizing coinjection and stretch blow molding for multilayer plastics

Considering the following configuration, it is a unique method that is only used to create multilayer bottles: polymer-barrier substance-polymer configuration. Sequential administration and simultaneous injection are the two forms of injection. Each layer is placed one after the other in sequential injection. For example, a barrier resin may come before a PET layer, which may subsequently be followed by another PET layer. On the other hand, concurrent injection mounding entails simultaneously injecting barrier resin and PET onto a PET preform, with the resin serving as the intermediate layer [71]. Large-scale applications of all the aforementioned processes enable high process flexibility and cheap production costs. Both multilayer flexible films and partially stiff packaging, including bottles, are made using the previously outlined methods.

3.3. Surface treatment

Various encasing techniques can also be used to create multi-layered sheets. Examples include vacuum, hot breakdown, aqueous disbandment, extrusion, solvent-based coatings, and wax [63]. Two of the most commonly used pairings are PE/board and PE/paper. Similar to securely connected laminated material, solvent-based lamination involves spraying the coating's solvent over the web-like material before it is cured in a hot oven. Hot air, aqueous dispersions, or ultrasonic heating and cooling methods are commonly employed in the infrared scenario. Vacuum coating is an entirely different kind of coating than previous coating methods. The method works by creating a strong vacuum through the evaporation of the substance, which allows the vapors to be evenly distributed over the moving web. Aluminium is the most common supply material for the aforementioned coating type, which is widely used in the production of metallised films. Layers of metal provide protection from light, gases, moisture, odour, and scent. Furthermore, silicon oxide or aluminium are the primary materials needed to make transparency films. The thickness of protective coating's usually ranges from 40 to 100 nm. The hoover coating method allows for coating one reel of web at a time in batches. The base materials most commonly used in this process are thin films, usually 15 or 20 μm oriented polypropylene (OPP) and 12 μm oriented polyethylene terephthalate (OPET) [72].

3.4. Plastic surface laminating

Multilayer films can be laminated to make them more robust, long-lasting, aesthetically pleasing, and useful. Laminates can be mass-produced through several techniques, such as extrusion, adhesive bonding, hot melt lamination, wax application, and others. In the extrusion lamination process, a primary web material is fed through a roller, where it is coated with a molten polymeric layer. This layer may be polymeric or non-polymeric, such as paper-based, depending on the process requirements. An example of this process is the use of extruded LDPE (Low-Density Polyethylene) between the primary and secondary webs during lamination. Each of the three layers is then compressed by a chilled drum with the help of an impression roller. An adhesive, either chemical or water-based, is applied to a primary layer and allowed to cure. Dry bond lamination is the term for this method. However, since the adhesive used in solvent-free lamination is rigid and does not require dehydration, a small volume of heating is advised to lower the adhesive's viscosity and enhance its adhesion [73].

3.5. Layer-by-Layer Fabrication (LBLF)

This method involves gradually condensing various film-forming ingredients onto a surface to create multi-layered coatings. Using the electrostatic charge attraction between subsequent layers of material is one of the most popular techniques for creating this kind of film or coating. The simplicity and cost-effectiveness of layer-by-layer (LbL) assembly are increasingly recognized as advantageous compared to traditional multilayered plastic (MLP) manufacturing techniques. LbL assembly is a method of creating complex structures by sequentially depositing layers of materials, often using non-covalent interactions such as electrostatic forces, hydrogen bonding, or van der Waals forces. This approach can be particularly beneficial in the context of polymer-based materials, as it allows for precise control over the thickness, composition, and properties of each individual layer. Unlike traditional MLP manufacturing methods, which often require complex processing and expensive machinery (such as co-extrusion or lamination), LbL assembly allows for the layer deposition to occur in a relatively straightforward and low-tech environment. This simplicity leads to reduced operational complexity and less dependency on specialized equipment. The ability to create multilayered structures using inexpensive materials and scalable processes makes LbL assembly more cost-effective than conventional MLP manufacturing techniques. LbL assembly can be carried out in a more controlled environment, with potentially lower energy consumption and material waste, further reducing the overall cost. Due to the interaction between the negatively charged substrate and the positively charged chemical solution, the chemical compounds are attracted to the substrate's surface. Once the excess solution is removed, the newly created positively charged substrate is dipped into a fresh solution containing positively charged components, leading to the formation of a new layer. This process can be repeated to create multilayer films [74]. In addition to electrostatic attraction, molecular interactions such as covalent and hydrogen bonds, and hydrophobic interactions can also contribute to the formation of layer-by-layer (LbL) films or coatings. The chemicals utilized to create the packaging with biodegradability have an impact on the interactions. For instance, a combination of electrostatic, covalent, hydrophobic and hydrogen interactions frequently create links between protein molecules [75].

3.6. Electrohydrodynamic process

The electro-hydrodynamic method uses a high-voltage electric field to atomize polymer solutions, producing fibers or particles at the micro or nanoscale. Electro-spinning and electro-spraying are two technologies that are frequently employed in the electro hydrodynamic process [68]. Due to its increased material content, huge surface area, and excellent polymer orientation, electrospun packaging is utilized for an extensive range of food-related applications. Electrospinning has been discovered to improve the mechanical, optical, and functional qualities of multilayer packaging layers. The electrospinning process generally utilizes a metal energy storage better elongation device, an injection pump, a high-voltage power supply, and a capillary tube with a nozzle. While electrospinning and electromagnetic spraying share many similarities, electrospinning differs in that it carefully selects the polymer solution and operating conditions to ensure the stability of the formed cone jet, preventing it from elongating [76].

3.7. Management of recyclate-based production methods under international standards

The incorporation of recyclates in plastic products requires adherence to international regulatory frameworks to ensure material quality, safety, and sustainability. ISO 15270:2008 [77] provides comprehensive guidelines for the recovery and recycling of plastics, emphasizing the need for traceability, contamination control, and quality assurance at every stage of the recycling process. Regulatory bodies such as the U.S. Food and Drug Administration (FDA) have also established specific guidelines for the use of recycled plastics in food-contact applications, requiring stringent safety assessments, including migration testing and chemical characterization, to prevent potential health risks [78].

A primary challenge in using recyclates is the variability in feedstock composition, as post-consumer plastics often contain a mix of polymer types, additives, and contaminants. This inconsistency can lead to processing difficulties, affecting mechanical properties such as tensile strength, impact resistance, and thermal stability [79]. Additionally, repeated recycling cycles accelerate polymer degradation due to thermal and mechanical stresses, causing chain scission, oxidation, and loss of molecular weight, which further limit recyclate applicability in high-performance sectors.

Regulatory restrictions are particularly stringent in applications requiring high purity, such as medical devices and food packaging. For example, the European Food Safety Authority (EFSA) mandates extensive decontamination validation for recycled PET used in food packaging, ensuring that contaminants from previous uses do not compromise consumer safety. Economic factors also influence recyclate adoption, as fluctuations in virgin polymer prices, coupled with the high costs of advanced sorting and purification technologies, impact the competitiveness of recycled plastics. Addressing these challenges requires ongoing advancements in chemical recycling, compatibilization strategies, and policy support to enhance the circularity of plastics and promote sustainable material management [79].

4. Approaches to end-of-life disposal of multilayer plastics

The recovery of multilayer plastics (MLPs) from consumers remains one of the most significant challenges in the recycling of these materials. MLPs are commonly used in packaging due to their ability to combine different material properties, but their complex structure makes them difficult to recycle. Effective recovery methods require efficient collection, sorting, and separation technologies. Specialized collection systems, such as curbside pickup or drop-off points, are essential for gathering MLPs separately from other waste streams. Sorting technologies, including mechanical, optical, and manual sorting, help to segregate MLPs based on material properties like size, shape, and composition. However, separating the individual layers of MLPs is one of the most complex tasks, often requiring advanced methods like density separation, solvent-based techniques, or chemical recycling processes

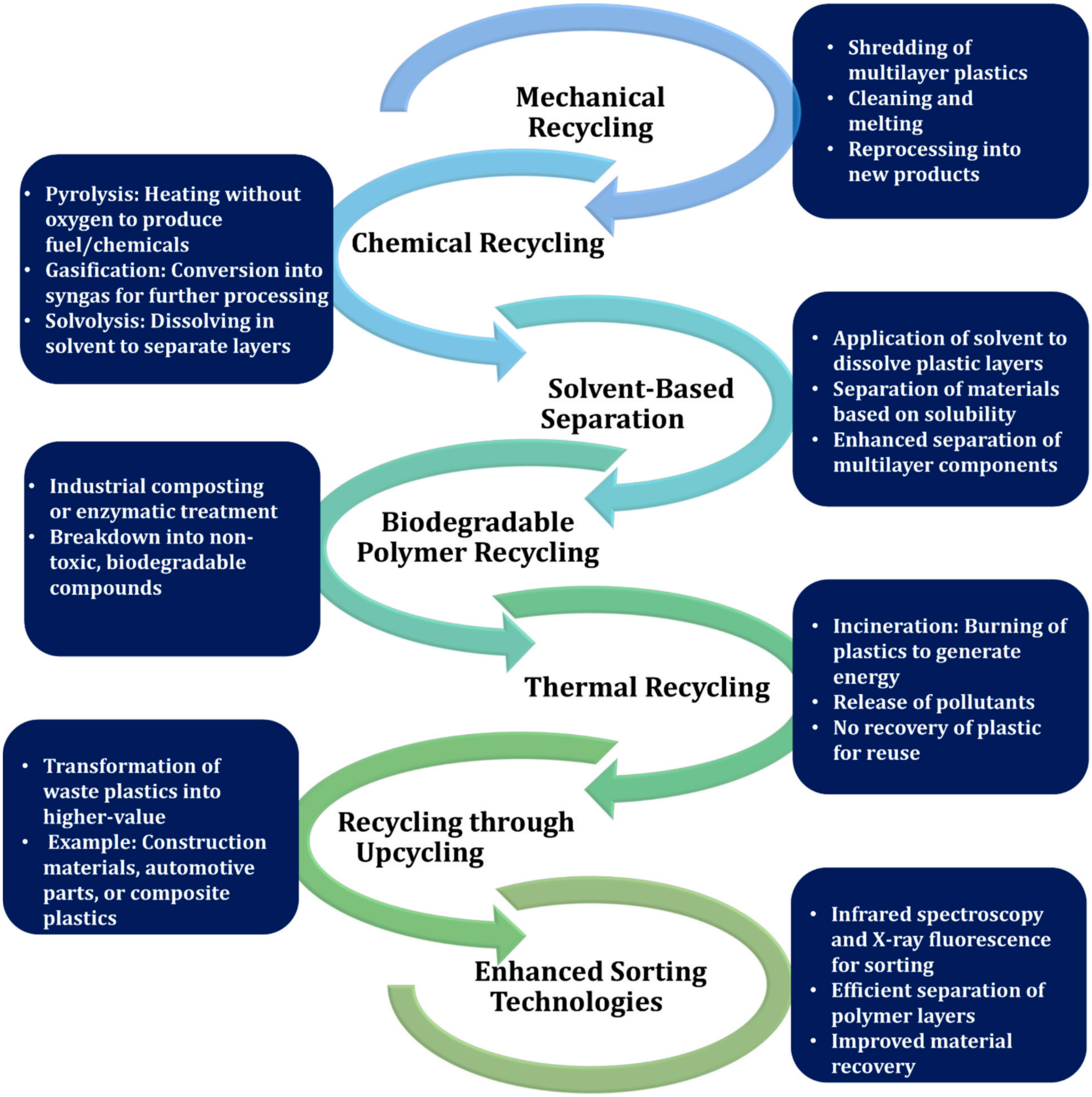

Fig. 6. Recycling Technologies for multilayer plastics.

such as pyrolysis or depolymerization. These advanced technologies are being explored to break down MLPs into their constituent polymers, which can then be reused. Moreover, extended producer responsibility (EPR) programs can play a crucial role by encouraging manufacturers to contribute to the waste management system, thus improving collection systems for MLPs. Despite these efforts, challenges remain in ensuring the efficiency and scalability of recovery processes, as well as in educating consumers about proper disposal practices. Therefore, continued research and innovation are needed to develop cost-effective and sustainable solutions for the recovery and recycling of MLPs. Chemical recycling is the third technique, which entails turning waste polymers back into their oil or hydrocarbon component especially for polyolefins or into monomers for polyesters and polyamides. Fig. 6 shows a variety of multilayer plastic recycling.

To achieve effective recycling outcomes, focus on sorting and reprocessing multilayer packaging materials in this section [80]. A sorting strategy is shown in (Fig. 7), highlighting the significance of this step in the disposal and reuse cycle [81]. The first technique is energy utilisation, which entails burning the polymers to transform their energy into energy that is electrical or thermal. The second technique, mechanical recycling, seeks to maintain the polymer chains while creating new goods was accomplished by physically processing polymer waste by methods like melting, dissolving, or shredding systems.

4.1. Mechanical recycling

The process of mechanical recycling is the most widely used method for recycling plastics and involves several crucial steps. These steps include screening, collecting, sorting (which can be done either manually or automatically), washing, extrusion, shredding, and granulation. Each of these stages plays an essential role in ensuring that the plastic material is processed efficiently and can be reused in new applications. However, the effectiveness of mechanical recycling depends on factors such as the type of plastic, the level of contamination, and the efficiency of sorting and cleaning processes. By optimizing these stages, mechanical recycling can significantly contribute to reducing plastic waste and promoting a circular economy (Fig. 8).

Thus, recycled plastics can help reduce CO_2 emissions and fossil fuel usage [82]. The sorted fractions are ground up and remelted in an extruder during reprocessing, with the addition of auxiliary materials like stabilizers and antioxidants. The polymerisation energy of the material is preserved during the mechanical recycling process. The recycling is of acceptable quality even though thermal–mechanical degradation occurs gradually. In their assessment of the mechanical removal of packaging materials such as PET, PP, PS, PE, and PVC, Schyns and Shaver (2021) [83] discovered that reprocessing led to polymer deterioration, requiring procedures and tactics to enhance recycling. Different processes of polymer degradation exist, and altering the chain's mechanical properties and length presents a technological challenge. Low cost, loss of mechanical qualities, and uneven product quality are associated with mechanical recycling processes [84]. Turriziani et al. (2023) used recycles to investigate the two multilayer films recyclability for meat packaging: PE/PE/ad/PA/ad/PE/PE (Film A) and PE/ad/PA/EVOH/PA/ad/PE (Film B). After conducting an extrusion recycling process, they discovered that recycling these packages appeared to be possible with the use of a commercial compatibilizers

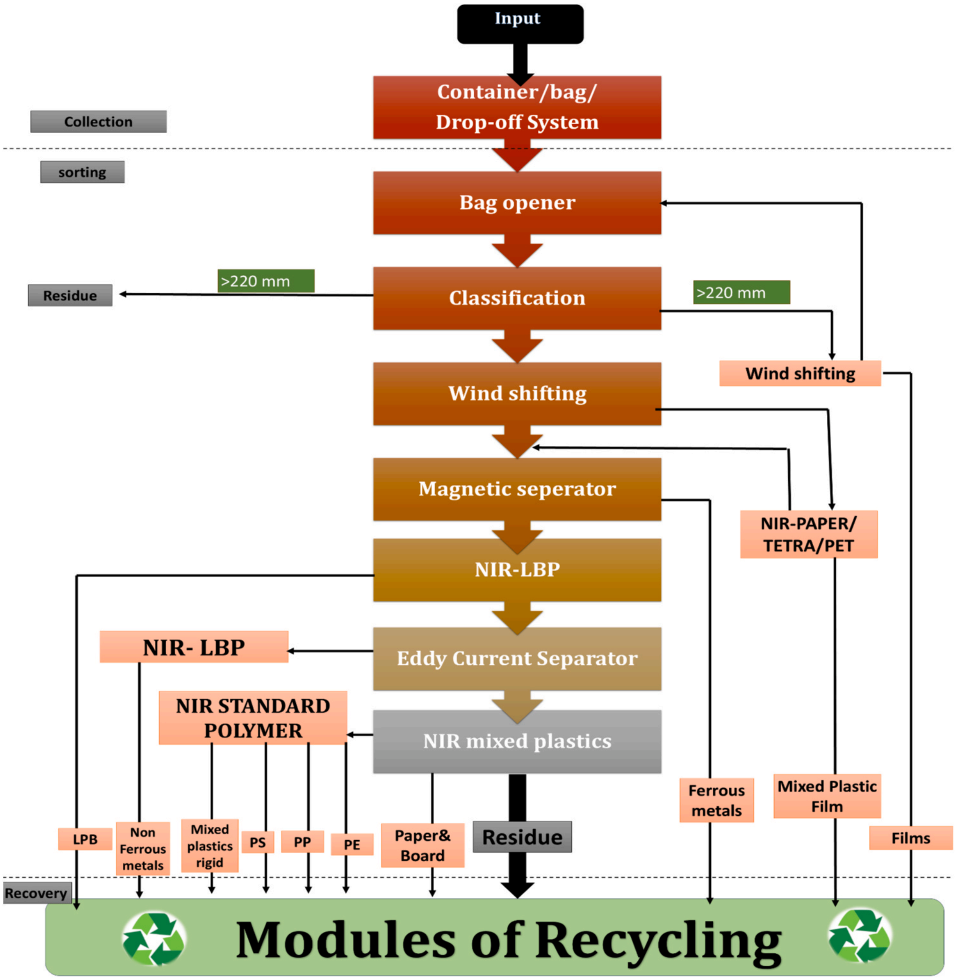

Fig. 7. Scheme of a standard state-of-the-art sorting plant. Adapted from [21]. NIR is the abbreviation for near infrared.

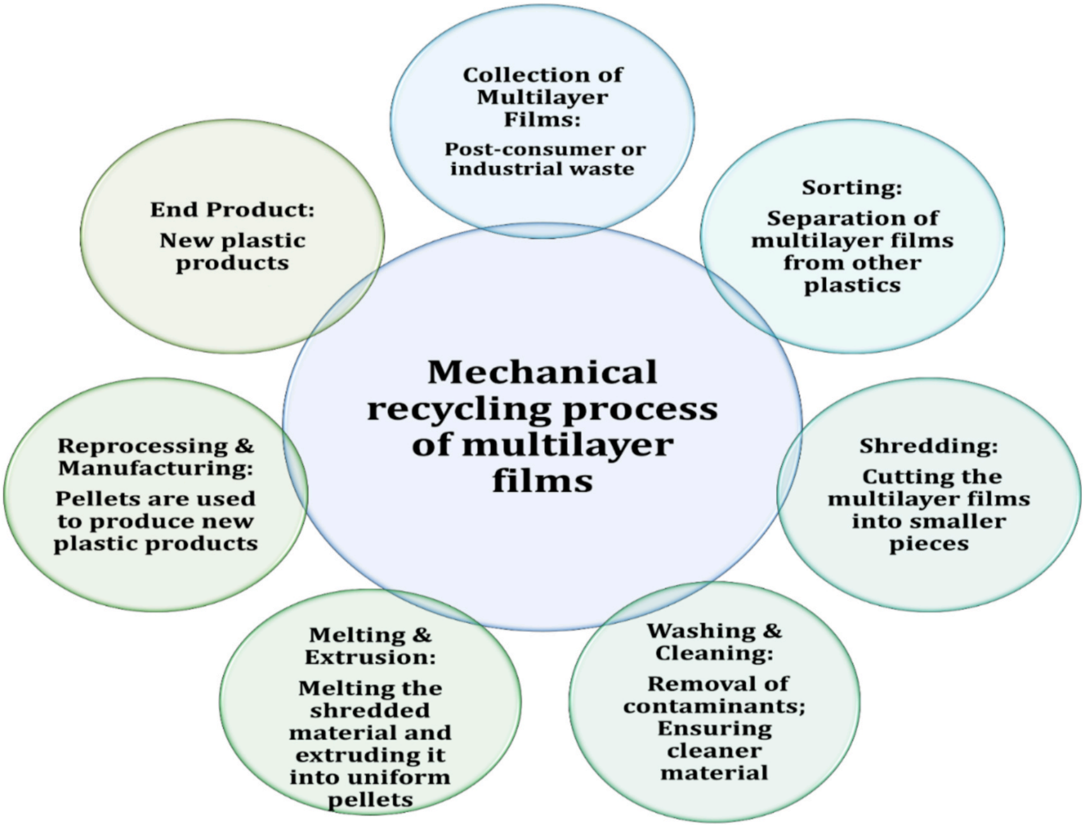

Fig. 8. Mechanical recycling process of multilayer films.

based on maleic anhydride (MA). Better elongation at break was demonstrated by the compatibilizers-containing films [85]. The results demonstrated by Kai-qiang Sun et al. (2019) that the elongation at break of chitosan/starch blend films was significantly enhanced by optimizing the plasticizer type, concentration, and chitosan-to-starch ratio. Specifically, the elongation at break reached 104.1 % when chitosan was plasticized with 10 % glycerol and 0.94 % ethylene glycol alone, with a blend ratio of 1:0.6 chitosan–starch. This represents a considerable improvement in mechanical properties, as compared to films without optimized plasticization [86]. These findings are presented in Table 7.

To develop separable multilayer packaging, a modified packaging adhesive was utilized in conjunction with a related recyclable procedure. Typical multilayer structures, such as PET/PE, PET/Al, and PE/Al, were fabricated by cross-linking furan-/maleimide-functionalized polyurethane (PU) prepolymers with a curing agent. These structures achieved adhesion strengths of up to 3 N per 15 mm specimen, demonstrating robust bonding performance. The key innovation lies in the adhesive's ability to dissolve when the laminate is heated in dimethyl sulfoxide (DMSO). This process enables straightforward separation and recovery of pure PE, PET, and aluminum foils without leaving any residue, making the method efficient and environmentally friendly.

Table 7
Elongation at break for chitosan/starch films with different plasticizing components [86].

Plasticizer Composition	Chitosan: Starch Ratio	Elongation at Break (%)	Standard Deviation (%)
No Plasticizer	01:00.6	35.4	2.3
Glycerol 10 % + Ethylene Glycol 0.94 %	01:00.6	104.1	3.1
Glycerol 10 %	01:00.6	82.6	2.9
Ethylene Glycol 0.94 %	01:00.6	76.2	2.7

Further, to enhance compatibility between polyolefins and other components, PE/PP-g-MA grafted polyolefins were employed, which can be physically and chemically attached to improve recycling outcomes. Uehara et al. demonstrated the use of PE-g-MA to recycle plastic sheets containing PE (70 %), PET (10 %), PA-6 (10 %), adhesives (10 %), and ink. The recycling process involved sequentially compatibilizing the PA component first, followed by the PET component. The mechanical properties of the PET component were dependent on the PE-g-MA content. At lower levels (3–5 %), the mechanical characteristics of the PET component remained poor. However, increasing the PE-g-MA content to 5–10 % significantly improved the mechanical properties, highlighting the critical role of compatibilizer concentration in optimizing material performance during recycling [87,88].

4.2. Chemical recycling

Chemical depolymerization is a promising alternative to mechanical recycling for plastics, offering the potential to convert polymers back into their original monomers in a closed-loop process. This approach supports the circular economy by facilitating the recycling of plastics into high-value compounds. The main chemical recycling techniques are divided into three categories: enzymatic depolymerization, thermochemical catalytic depolymerization, and solvolysis (which includes methanolysis, hydrolysis, and glycolysis) [89]. Enzymatic depolymerization uses specialized enzymes to break down polymers such as PET into their monomers under mild conditions, making the process environmentally friendly. Thermochemical catalytic depolymerization involves the use of heat and catalysts to break down plastics like PE, PP, and PET into smaller molecules or chemical feedstocks, which can be further processed or used as fuels. Solvolysis techniques, including methanolysis, hydrolysis, and glycolysis, involve the use of solvents to depolymerize plastics like PET into their monomers. These methods allow the recovery of valuable monomers, which can be reprocessed into new polymers or other useful products [90]. Huang et al. (2022) highlight that integrating chemical recycling with enzymatic degradation could enhance material recovery and contribute to circular economy strategies. However, key challenges—including high energy consumption, process scalability, and economic feasibility—still hinder widespread industrial adoption. Their review of life cycle assessment (LCA) studies indicates that chemical recycling offers significant reductions in greenhouse gas emissions compared to conventional waste management methods, particularly incineration. Despite its potential, further advancements in catalyst design, process optimization, and supportive regulatory frameworks are essential to improve efficiency and ensure the long-term viability of chemical recycling technologies [91]. Innovative chemical recycling methods for plastic packaging materials like PE, PP, PET, and PS have been developed, contributing to the upcycling of waste polymeric materials into high-value compounds (Table 8), further advancing sustainability in the plastic industry and promoting a circular economy.

4.2.1. *Recycling polymers through selective dissolution and re-precipitation*

Selective dissolution and re-precipitation offer a promising approach for recycling polymer mixes, enhancing the efficiency of recycling multilayer structures. The method entails dissolving different polymers in a mixture one after the other at particular temperatures. Interestingly, this method has been effectively used for a variety of multilayer structures, such as PA-6/Tie/EVOH/EVA/Surlyn, Tie Layer/EVOH/Maleated-PP, Tie Layer/PP, and PP/Maleated-PP [104]. A highly effective method designed for managing garbage including polymers was presented by Mäurer et al. (2012); it is especially well-suited for recycling packaging. This method effectively allowed for the recovery of PE, producing material of quality which is similar to virgin material, although the components that is not dissolved endured as low-value residue [105]. A four-step procedure was developed by Lindner et al. (2004) to extract LDPE from pre-sorted plastic films: removing the ink, removing low-molecular-weight components, combining the film's constituents, resulting in, removing unwanted polymers that are and recovering LDPE from the mixture [106]. A notable method with significant application focused on recycling PA-6 and PA-6,6 from mixed polyolefin polymer waste. This process involved heating the waste above the polymer's melting point and mixing it with an ester-based solvent. The molten polyolefin phase was then isolated from the ester solvent mixture using methods like centrifugation, filtration, decantation, skimming, or a combination of these techniques [107]. The primary benefit of the dissolution-re-precipitation method is that it eliminates the need for a time-intensive sorting process, which typically involves various multilayer and non-multilayer packaging systems. A novel recycling technique developed by Samorì et al. specifically for multi-layered materials containing PE and Aluminium [108]. In order to recover metal and plastic components, they employed N, N-dimethylcyclohexylamine (DMCHA), that will be modified by using CO_2, and solvents with switchable hydrophilicity. Comparably, other research on mixed textile waste has shown that, depending on the supplementary materials in the waste stream elastane can be recovered by selectively dissolving with used solvents like gamma-valerolactone (GVL), tetrahydrofurfuryl alcohol (THFA), cyrene, dimethylacetamide (DMCA),

Table 8
Processes, catalysts, and applications in the recycling and modification of PET, PCL, PLA, PBT, and multilayer packaging.

Process	Reaction Components	Main Products	Typical Temperature	Typical Catalysts	Applications	References
Hydrolysis of PET	Polyethylene Terephthalate + H_2O	Terephthalic Acid (TPA), Ethylene Glycol (EG)	180 °C – 250 °C	Acid catalysts (e.g., H_2SO_4), Base catalysts (e.g., NaOH), Enzymatic catalysts	TPA and EG recovery for new PET production	[92]
Aminolysis of PET	PET + R-NH_2	Polyamide (e.g., Nylon)	180 °C – 230 °C	Amines (e.g., Hexylamine, Ethylamine), Acid/Basic catalysts	PET recycling for polyamide synthesis	[93]
Glycolysis of PET	PET + $HOCH_2CH_2OH$	Bis(hydroxyethyl) Terephthalate (BHET)	200 °C – 250 °C	Zinc acetate, Sodium acetate, Manganese acetate	PET recycling for BHET reuse in PET manufacturing	[94]
Hydrogenation of PET	PET + H_2	Hydrogenated PET	150 °C – 250 °C	Metal catalysts (e.g., Pt, Pd, Ni, Ru)	Thermal stability and chemical resistance improvements in PET	[95]
Hydrosilylation of PCL	Polycaprolactone + $(CH_3O)_3SiCH{=}CH_2$	Silane-modified PCL	150 °C – 200 °C	Platinum-based catalysts (e.g., Karstedt's catalyst), Tin-based catalysts	Surface modification for better material compatibility	[96,97]
Hydrosilylation of PLA	Polylactic Acid + $(CH_3O)_3SiCH{=}CH_2$	Silane-modified PLA	150 °C – 200 °C	Platinum-based catalysts, Tin-based catalysts	Surface modification for compatibility and durability	[98,99]
Hydrosilylation of PET	PET + $(CH_3O)_3SiCH{=}CH_2$	Silane-modified PET	150 °C – 200 °C	Platinum-based catalysts, Titanium-based catalysts	Enhanced surface properties and material interactions	[100]
Hydrosilylation of PBT	Polybutylene Terephthalate + $(CH_3O)_3SiH$	Silane-modified PBT	150 °C – 200 °C	Platinum-based catalysts, Tin-based catalysts	Improved performance in composite applications	[98]
Pyrolysis of Waste Multilayer Packaging	Biaxially Oriented Polypropylene/Metallized Films	Oil, Gas, Char, Monomers (e.g., TPA, EG)	350 °C – 500 °C	Metal oxide catalysts (e.g., ZnO, Al_2O_3), Zeolites	Multilayer packaging recycling for monomer and energy recovery	[25]
Laminated Metallized Recycled Plastic	BOPP + Aluminum Coating + PET	Recycled Plastic Materials	250 °C – 300 °C	Acid/base catalysts, Thermal catalysts	Conversion into new plastic materials	[101]
BOPP/MET/BOPP Recycling	BOPP + Aluminum Layer	Recycled BOPP or Hybrid Films	250 °C – 270 °C	Solvents (e.g., toluene, xylene), Metal-based catalysts	Reuse for packaging and material production	[102]
BOPP/MET/BOPP + Polyolefinic Mixed Plastic Waste Recycling	BOPP + HDPE + LDPE + Aluminum	Mixed Recycled Plastics (e.g., Polyolefins, Hybrid Materials)	270 °C – 300 °C	Thermal catalysts, Solvents, Metal oxide catalysts	Recycling multilayer films and polyolefinic waste	[103]

dimethylformamide (DMF) or n-methylpyrrolidone (NMP). There are further uses for the polymers that are recovered via the dissolution-precipitation process [109]. By employing a green solvent called p-cymene, Cavalcante et al. (2022) recently shown how to dissolve PP from disposable face masks. The recovered PP was then utilised to create membranes for organic solvent nanofiltration [110]. It has also been demonstrated that other green solvents, like α-pinene and D-limonene, may dissolve polyolefins, making them suitable for use in comparable membrane applications. Recent research has highlighted the increasing focus on solvent extraction recycling technologies and their application to recover the numerous components typically present in diverse plastic waste streams [111]. While selective dissolution has shown great promise, it is important to acknowledge its challenges. The use of large amounts of solvent, many of which are toxic and regulated, remains a significant drawback. Additionally, the need for solvent recovery and the development of safer, more sustainable solvents are critical to making this method more environmentally friendly. Efforts are ongoing to address these concerns by exploring greener solvents and improving solvent recovery techniques.

4.2.2. *Delamination of multi-layer plastic*

According to Mukhopadhyay et al. (2004), the binder glue can be selectively dissolved using 50–70 % nitric acid without compromising the aluminium or plastic components. Water-resistant labels that are simple to remove in alkaline conditions have been made using alkali-soluble polymers [112]. Because of the strong layer adhesion in multi-layer packing, mechanical delamination by impact is less frequent. Multilayer packaging can also be recycled and delaminated using chemical decomposition techniques. Patel et al. (2016) utilized highly concentrated H_2SO_4 to decompose the PET component in multilayer packaging of PET/PE, whereas preserving the PE film [113]. Similarly, Kulkarni et al. (2011) suggested a method using subcritical and supercritical water to break down polymeric materials and isolate pure aluminum from plastic-aluminum composite packaging [114]. Enzymatic detergents containing protease have been employed to facilitate the separation of protein-containing layers from plastic substrates, permitting for layer separation based on differences in density. Additionally, delamination technique investigated for multilayer packaging with aluminum sheets. Lee et al. (2006) introduced recycling techniques for multilayer packaging by dissolving selectively the intermediate layer of aluminum. This process involves reacting aluminum with an acid or alkali solution, which causes the aluminum to dissolve into an aqueous solution. Consequently, the layers, such as PET, PP, and PE, can be separated according to their density differences [115].

The method for recovering multilayer constructions made of polymers, aluminium, and paperboard using a simple solution is explained. The aluminium is extracted as a salt that dissolves in water. When layers are too thin or misaligned, techniques like separation based on density, electrostatic separation, and melt filtering that is necessary, though they often present significant challenges [116]. Waste from flexible packaging was delaminated using switchable anionic surfactants (SAS) for the purpose to be recycled. Highly efficient methods for separating multilayer plastic garbage containing aluminium were created utilising C12-TEA. As a consequence, even from problematic trash like PE/aluminum/PET materials namely coffee packing bags (PO/aluminum/PET and PP/aluminum), non-oxidized aluminium and polyolefins with optimal thermal and mechanical qualities were recovered. PE may be effectively separated from food and beverage cartons using C12-TEA. Although other components appeared more difficult to separate, the recovery of polyolefins showed encouraging results [117]. Tamari Mumladze et al. (2018) investigated a sustainable, environmentally friendly recycling method for multilayer flexible packaging waste (MFPW) by combining ultrasonic treatment with switchable hydrophilicity solvents. This approach aimed to enhance the separation and recovery of valuable components from the packaging waste in a sustainable manner. This approach enabled the recovery of all components, including 14.2 % aluminium and 85.3 % polymeric materials by weight, achieving a recycling efficiency of over 99 %. For powder metallurgy applications, aluminum was recovered in 100 μm flake form, while mixed polymers—including paint, adhesive, ink, EVA films, PE powder, and PET films—were gathered for use in lightweight applications [25].

4.2.3. *Hydrolysis of PET*

While hydrolysis reactions consume more energy, they are regarded as a greener alternative to other solvolysis methods [118]. Alkaline, neutral, or acidic environments can be used for them. Neutral hydrolysis of PET (polyethylene terephthalate) occur at temperatures higher than 265 °C along with the water or PET (w/w) ratio larger than 5.1/1. Catalytic amounts of zeolites, organophosphorus compounds, or alkali metal acetates can greatly speed up the process. Colnik and his colleagues recently shown that PET bottles, both colourless and coloured, may be hydrolytically recycled in sub critical and supercritical water at temperatures around 250 and 400 °C in 1–30 min. The highest amount of terephthalic acid (TPA) was produced in 30 min at 300 °C, with nearly 100 % purity [119]. A mathematical model suggests that ocean salt is an effective neutral catalyst that accelerates breakdown of PET, particularly in tropical regions.

The initial stages of acid hydrolysis of PET involve breakage of chain at elevated temperatures and degradation by concentrated acids such as H_3PO_4, H_2SO_4, and HNO_3. However, unlike these acid processes, alkali-catalyzed PET depolymerization, which has been widely studied, typically uses both organic and inorganic bases [120]. Multilayer packing films were found to degrade when exposed to a very acidic sauce. An experiment was conducted to explore potential alternatives to Barex for use in extremely acidic sauces [121]. To study the degradation behavior of multilayer films, two commercially available types—polyethylene terephthalate/ink/adhesive/ polyamide/ adhesive/polypropylene and polyethylene terephthalate/waste low-density polyethylene/aluminum foil/ adhesive/ polyester/low-density polyethylene—were placed in hot sauce. The research also included tests on a monolayer Barex® (acrylonitrile methyl acrylate copolymer) screen. The findings revealed that while NaCl solutions did not degrade the multilayer films, both hot sauce and acetic acid solutions causes delamination and oxidative degradation. Two important discoveries were also emphasised by the study: 1) Hot sauce's acidic ingredients oxidise polyethylene and turn aluminium foil into a soluble salt; 2) corrosion of the surface is a major factor in polyethylene oxidation.

4.2.4. *Glycolysis of PET*

BHET, a monomer that is a helpful starting material for PET upcycling, is produced during the digestion of glucose. Various catalysts derived from orange peel ash were utilized to initiate the glycolysis process of post-consumer PET waste. After 90 min of complete PET depolymerization, 80 % BHET was obtained. The catalysts remained active for up to five cycles before showing significant deactivation. Unlike traditional organometallic complexes, glycolysis assisted by organo-catalysts is considered to present new opportunities for an environmentally friendly plastic recycling method [122,123]. The application of 1,3-dimethylimidazolium-2-carboxylate as organo-catalyst in the PET glycolysis showed promising results. The researchers successfully converted PET into BHET (bis(hydroxyethyl) terephthalate) by functionalizing silica-coated, magnetic Fe_3O_4 nanoparticles along with the Fe-based ionic liquid. The depolymerization process was completed in under an hour at 180 °C, resulting in the BHET yield (60 %), which was attained through precipitation after cooling the reaction mixture. Because of their magnetic properties, these catalysts are easily recyclable and can be recovered efficiently, with the end products showing no metal contamination [124].

4.2.5. *Aminolysis and methanolysis of PET*

Although aminolysis provides better energy and sustainable ecofriendly advantages, the production method is costlier due to the usage of ionic liquids based on ammonium. Very short depolymerisation periods offset the high temperatures required for aminolysis because of the accelerated reaction speed. However, terephthalamides are produced when PET is depolymerised by aminolysis, and these compounds have few economic uses. PET has been aminolyzed using a variety of amines, including monoethanolamine (MEA), both with and without catalysts including ionic liquids, metal salts, and quaternary ammonium compounds [125]. Microwave-induced aminolysis of PET without catalyst was discovered to be an effective technique for recovering various terephthalamides, starting with ethanolamine, allylamine, hexylamine, or furfurylamine, offering excellent selectivity and yields. To create high-quality films, terephthalamides were used [126]. Additionally, using a variety of organocatalysts and different amino-alcohols, it was possible to aminolytically upcycle PET post-consumer waste to form diol terephthalamides, which were then used to create poly(esteramides).

This problem might be resolved by chemical depolymerisation, which yields superior monomers and oligomers [127]. Regenerating DMT, TPA, EG, BHET, or other chemicals is the key objective of PET chemical recycling. The primary by-products of PET methanolysis, a degrading process that is typically carried out at high pressure of 2–4 MPa and high temperatures of 180–280 °C are DMT and EG, and it has substantial start up and running costs. However, Pham and colleagues have discovered a low-energy catalysed methanolysis process that, when K_2CO_3 is present as a catalyst that converts PET into DMT at ambient temperature. Although the total reaction period is 24 h, PET resins entirely break down into monomers with great selectivity in DMT at 25 °C with yield of 93.1 % [128]. A novel technique for the post-consumer PET trash methanolysis in the presence of sodium hydroxide has also been disclosed by Myren and colleagues. Overall yields of 65 % in TPA was successfully achieved under microwave irradiation, and the method can be performed in either a microwave reactor or electrochemical reactor with mild reaction conditions (85 °C, 40 min) [129]. The low boiling point of alcohols necessitates high-pressure reactors, making alcoholysis the most energy-intensive process, according to the data gathered. The most energy-efficient method for producing high-quality DMT was identified as the breakdown of PET through methanolysis in the presence of a ZnO nanodispersion. Surface alcoholysis modification is a simple and cost-effective technique for PET improved its wettability and enhance the sink-float separation from materials like PVC, PS, and PMMA which is hydrophobic in nature [130]. An organocatalyst made from basic reagents, including tetramethylammonium hydroxide and dimethyl carbonate, $[NMe_4]^+[OCO_2Me]$-, facilitated another promising case of PET methanolysis, with mild reaction conditions and yielding high amounts of DMT. Otherwise, ionic liquids (ILs) based on imidazolium metals can perform equally well or even better than $[NMe_4]^+[OCO_2Me]$- [131].

4.2.6. *Catalytic depolymerization*

Plastic depolymerisation caused by various catalysts, that includes metal catalysts in a hetero or homogeneous phase, bases, enzymes, extremely acidic minerals, and organocatalysts [132]. Through catalytic hydrogenolysis of polyethylene terephthalate (PET) utilizing homogeneous Ru-PNN complexes of the Milstein type, a 99 % yield of 4-benzenedimethanol can be achieved. However, this technique is not effective for PP and PE. Conversely, Through competing decarboxylation and hydrogenolysis pathways, a Ru/Nb_2O_5 catalyst can produce hydrogen from ethylene glycol and post-consumer PET was converted into benzene, toluene, and xylenes. A carbon-based single-site molybdenum dioxo catalyst effectively hydrolyzes PET bottles into terephthalic acid (TPA) and ethylene, with an 87 % yield and strong stability [133]. Ruthenium nanoparticles supported on carbon with mild reaction conditions, can be used to create liquid alkanes from PET with a 45 % yield. Using heterogeneous catalysts like SnPt/-Al2O3 and Re2O7/-Al2O3, high-density polyethylene (HDPE) can be converted into linear alkanes. This process begins with the dehydrogenation of poorly reactive aliphatic substrates, followed by their functionalization or cleavage with a highly active olefin catalyst [134]. In the past, a number of methodologies has been tested for the depolymerisation of plastics, including PET, PVC, and polystyrene (PS). Heterogeneous catalysts are an appealing alternative for industrial application since they are typically easier to utilise and more economically viable than homogeneous ones. An alternate technique for the depolymerisation of PET utilising silanes and an economical, air-stable dioxomolybdenum complex was presented by Fernandes and associates in 2020.

Even under severe reaction conditions (160 °C, 4 days), the reductive cleavage of PET was successfully performed, resulting in a high p-xylene yield (65 %) when 5 wt% $MoO_2Cl_2(H_2O)_2$ and six equivalents of phenylsilane were used Fernandes also pioneered the hydrosilylation-based reduction of PET and other waste of plastics using the eco-friendly zinc catalyst Zn(OAc)2··2H2O, resulting in the production of valuable compounds like tetrahydrofuran, 1,2-propanediol, 1,6-hexanediol, and p-xylene. Under identical reaction conditions, the p-xylene yields were consistent with those achieved using molybdenum oxides, while the yield of ethylene glycol increased to 43 % [135]. Catalytic fractionation is a method utilized to break down of PET in multilayer packaging that includes C–C linked polymers namely as PE, ethylene vinyl alcohol, and ethylene–vinyl acetate. The method begins with deconstructing ester bonds, followed by a C–C bond-specific step, namely polyolefin hydrogenolysis [136–142]. In a hybrid open and closed-loop recycling method for mixed ester and ether-based polymers, Jehanno et al. (2021) applied this concept. They glycolyzed PET and bisphenol-based polycarbonate using an amine-based organocatalyst in their approach [143].

4.2.7. *Enzymatic catalysis*

The enzyme-mediated activity of a number of bacterial and fungal species for the various polymers degradation has already been evaluated [144]. The primary obstacle to the enzymatic breakdown of polymers like PE and PP is their intrinsic stability, inertness, and strong hydrophobicity. Thermal oxidation or UV pre-treatments, however, may make them more reactive. Sadler et al. (2021) [145] made a notable advancement by utilizing modified E. coli to produce vanillin and developing a new enzyme-catalyzed method for the post-consumer PET hydrolysis. Santacruz Juarez et al. [146] used molecular docking simulations to evaluate the enzymes activity namely unspecific peroxygenase (UnP), lignin peroxidase (LiP), manganese peroxidase (MnP), and laccase (Lac). They were able to forecast the binding energy, strength, and affinity between two molecules using this method. The findings showed that by accelerating consecutive degradation processes, synergistic enzymatic pairing which happens naturally increases the effectiveness of the catalytic process. The aluminium layer is dissolved and removed by acidithiobacillus ferrooxidans, while the remaining cardboard is entirely removed by biotechnological cellulases. More complicated polymer blends, like the sterile multilayer boxes with PET depicted in (Fig. 9), can also benefit from this creative method.

In addition to breaking down single polymers like polyester, microbes and their enzymes have enormous promise for recycling intricate multi-layered materials. For example, depending on the product for which they are intended, beverage cartons might consist of up to 7 or more layers of various materials, such as cardboard, aluminium, and plastics [147]. Levoglucosenone, caprolactam, furfural, and recycled PE were obtained by upcycling post-consumer cartons composed of paper, polyolefin, and polyamide using a THF/H_2SO_4 process followed by xylene fractionation. As an alternative, individual components are sequentially recovered from multilayer materials may be possible due to the great specificity of enzyme-microbe combinations [148]. An efficient and environmentally responsible technique for recycling multilayer waste materials containing metal is enzymatic-bioleaching recycling. Enzymes aid in the removal of fibrous residues and improve the final goods' purity. Aluminium is dissolved in just one week by sulphuric acid produced by biology without causing damage to

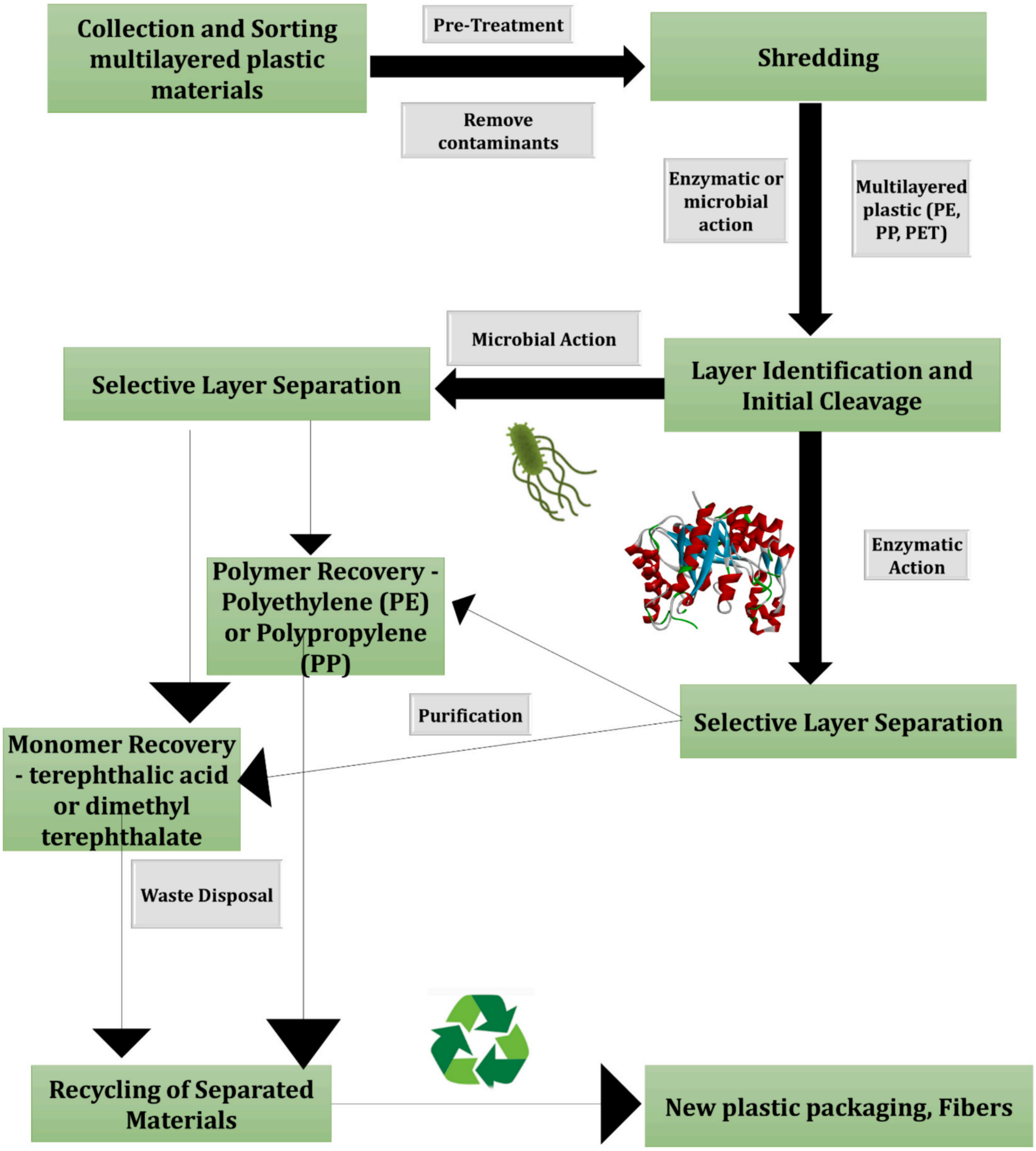

Fig. 9. Schematic presentation of stepwise enzymatic/microbial separation of multilayered.

polymeric structures. Pure polyethylene and aluminium hydroxide, the end products, can be recycled, reducing the need for incineration [149,150].

4.3. Energy recovery through thermochemical conversion of multilayer waste plastics

The process of thermochemically converting multi-layered waste plastics involves applying heat to induce chemical reactions, which transform these complex plastic materials into energy or valuable products. Due to their intricate composition, multi-layered plastics, utilized in packaging, recycling is difficult [151]. However, this conversion method presents a promising solution to overcoming these challenges.

4.3.1. Pyrolysis method

Pyrolysis method that converts waste plastic by heating to high temperatures (300 to 800 °C), in an oxygen-free environment. This method breaks down the plastics into different primary products namely gases, liquids (pyrolysis oil), and solids (char), that can be utilized further then processed. Multi-layered plastic waste, such as combinations of PP + PE, PP + PET, PET + PE, and PVC + PE, presents unique challenges for decomposition due to its complex composition [152]. These materials are frequently disposed of by burning them.

Multiple-layered polymers are pyrolyzed at temperatures between 280 and 800 °C without the presence of oxygen. However, because individual polymers have different melting points, reaching higher temperatures necessitates a significant energy input and complex reactions. Experimental results show that the amounts of various polymers affect the final composition in the feedstock, especially the liquid-to-gas ratio [153]. For instance, pyrolyzing a feedstock blend consisting of PET (20 %) and PE (80 %) at 440 °C produces a comparatively small volume of liquid (33 wt%), while at the same temperature, pure PE feedstock produces a much greater liquid output (70 wt%). The precise makeup of the waste polymers, especially the presence of PVC and PET, is essential to the method's efficacy [154]. At temperatures between 500–550 °C in a fixed-bed reactor, pyrolysis of mixed PE and PET yields pyrolytic oil with a density (0.74 g/cm3), a kinematic viscosity (5.77), and a HHV of 35.2 MJ/kg. When only PE undergoes thermal breakdown, the process produces liquid compounds within the C5–C25 hydrocarbon range, achieving a significant 70 wt% yield. However, only 4.7 wt% of C5–C20 hydrocarbon compounds are formed when PVC is used as the sole feedstock, resulting in fewer liquid products. While the products recovery from mixed polymers like PET, PP, PE, and PVC has been extensively documented, it is crucial to recognize that the quality and properties of mixed multi-layered waste plastics can differ considerably [155].

4.3.2. *Gasification*

Another thermochemical method is gasification, which entails heating the waste plastic while a regulated quantity of steam or oxygen is present. Syngas, a combination of hydrogen (H2) and carbon monoxide (CO), is produced during the process. The type of gasifier used, different operating parameters like temperature, equivalency ratio, gasifying agents (such as oxygen, steam, or air), gasification pressure, and the particular kind and calibre of waste plastics utilized as feedstock all affect the results of gasification processes. Zaccariello and Mastellone conducted a study examining the gasification of a feedstock made of waste PE + PP and PVC + PET in a fluidized-bed reactor. The producer gas generated had a low heating value (LHV) of 7.9 MJ/m^3, while the feedstock featured a higher heating value (HHV) of 42.69 MJ/kg, a bulk density of 590 kg/m^3, and an LHV of 36.95 MJ/kg. Impressive carbon recovery efficiencies (CCE) and hydrogen recovery efficiencies (HRE) of 84 ± 11 % and 91 ± 3 %, respectively, were reported by the study [156]. Furthermore, 75 4 % was the measured cold gas efficiency (CGE). These findings imply that a sizable amount of hydrocarbons were produced during the process of gasification, resulting in the creation of gas with a high specific energy content and calorific value.

4.3.3. *Hydrothermal liquefaction: A sustainable approach to waste plastic*

When exposing several synthetic and bio-polymers to a hydrothermal environment, a process known as hydrothermal liquefaction (HTL) has been studied for turning them into oil. Successful depolymerisation is mainly attained for particular polymer types, and the efficacy of HTL varies according to the polymer chains. Polymers that lack hydrolysis-active sites, such as PS (polystyrene) or polyolefins, are inert at subcritical water temperatures below 374 °C and 22.1 MPa, as they do not have heteroatoms in the carbon chain to facilitate hydrolysis [157].

However, in supercritical HTL conditions above 374 °C, they can be effectively transformed into oil with substantial yields. Condensation polymers with heteroatoms, like PET, nylon, and polyurethane, on the other hand, easily hydrolyse under subcritical circumstances, recovering their initial monomers. PET hydrolysis through HTL conditions has been studied extensively and is considered more efficient compared to other processes, as it operates under milder conditions. This makes it a promising approach for the recycling of PET [158]. Tito et al. (2023) developed and tested a two-stage HTL process for the recycling of chemical of a two-layer film composed of LLDPE/PET. Experimental results suggests that during the first subcritical stage at 325 °C, ethylene glycol (47 %) was extracted into the aqueous phase, and terephthalic acid (94 %) was recovered as a solid from PET fraction. The remaining PE which is unconverted was utilized as feedstock for a following supercritical HTL stage after 90 min at 450 °C, producing 47 % naphtha-gasoline oil and 29 % alkane-rich gas [159]. When LDPE/PA film was cured using HTP, the solid product mostly consisted of the LDPE fraction. In the liquid phase, 22 ± 3 wt% of the original film as caprolactam monomer was recovered and its related compounds [160].

4.4. *Latest innovations in multilayer plastic recycling technologies*

Recent advancements in multilayer plastic recycling technologies have focused on developing methods to efficiently recover individual polymer components from mixed plastic waste. These innovations aim to improve the efficiency and sustainability of recycling processes, particularly for multilayer materials that are difficult to separate and recycle using conventional methods.

4.4.1. *Selective dissolution and solvent systems*

One of the most promising approaches for recovering individual polymer components involves selectively dissolving the target polymer using specialized solvent systems. Notable technologies based on this approach are being implemented in Asia and Europe, including the Crea Solv Process, developed by Unilever and the Fraunhofer Institute, and APK AG’s new cycling process. These methods are particularly beneficial for reducing waste during the production of multilayer films, offering a more sustainable solution.

4.4.2. *STRAP process for multilayer film recycling*

Walker et al. (2020) introduced a computational platform strategy for breaking down multi-layered films of moderate complexity (three or more layers) into their constituent polymers are shown layer-by-layer Fig. 10. This is achieved using a variety of solvent washing techniques in a solvent-targeted recovery and precipitation (STRAP) method [161]. Both the solvent and solvent agent mixture and the key polymer layer have been recovered as a dry, transparent solid. The STRAP process could potentially recycle Amcor’s multi-layer film into pure chemicals at a cost compared to that of virgin materials.

4.4.3. *Challenges of contamination and resin properties*

In a study by Cecon et al. (2022), the STRAP approach was used to examine the physical properties of PET and PE recovered from two different multilayer films. The viscosity properties of the PE and PET resins recovered through the STRAP process were found to differ from those of the virgin resins originally used in the films. Contamination in the reclaimed resins, including the presence of tie layers (EVA and EVOH) in the multi-layer films, was confirmed by utilizing ATR-FTIR and Raman spectroscopy, respectively [162].

4.4.4. *Chemospecific depolymerization of PDKs*

Additionally, Demarteau et al. (2022) investigated the chemospecific depolymerisation of molecularly modified PDKs (polydiketoenamine resin powders) 1–4 to monomers in mixed-polymer and −material chemical recycling. In their process, feedstock was mechanically mixed and molded into two separate PDK nanoparticles under conditions of 20 kPsi and 140 °C for 20 min to produce a microstructured solid bar. PDKs 1 and 4 underwent two phases of depolymerisation. The study also covered the challenges of recycling trilayer systems, particularly due to the presence of tie layers, and discussed the use of consecutive deconstruction in strong acids at various temperatures to achieve chemo-specificity and orthogonality in multistage PDK disintegration [163].

4.4.5. *Use of formic acid for layer delamination*

According to Ügdüler S et al. (2021), formic acid, due to its smaller alkyl chain, provides a better environment for dissolving multilayer components. This study examined how formic acid was distributed across various multilayer sample layers at varying acid concentrations and temperatures. The rates of dissolved pure cured solvent-free (SF) and solvent-based (SB) polyurethane adhesives were investigated by adjusting the temperature between 60 and 100 °C with the different concentrations of acids from 60 to 100 vol%. Both temperature and the amount of formic acid present affected how quickly both adhesives dissolved [164]. A kinetic model was created to describe the delamination of multilayer flexible packaging films, demonstrating that all films were fully delaminated within 3000 s. The delamination process took the shortest period of time because of the constituent polymer layers’ higher diffusion coefficient.

5. Bio based packaging

An overhaul in the use of raw materials is required for an ecologically sound and environmentally friendly economy; the excessive use of raw materials derived from fossil fuels must be replaced with methods and components made from plant and other limitless resources [165]. Due to

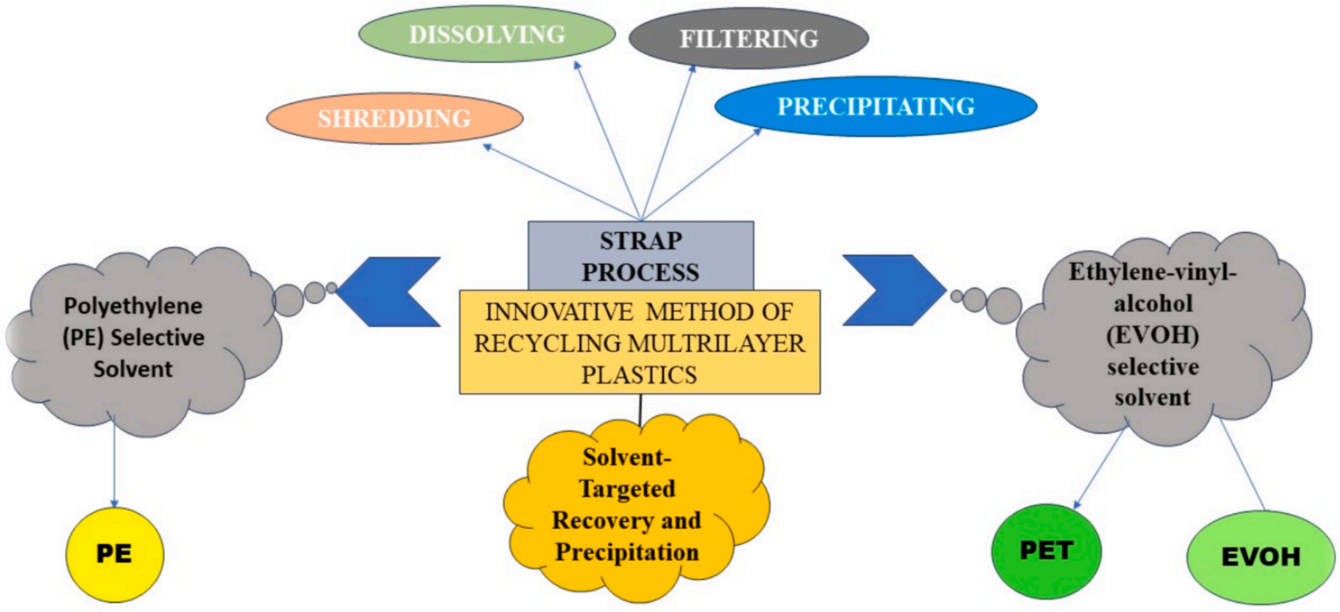

Fig. 10. Overview of the solvent-targeted recovery and precipitation (STRAP) process.

economic and environmental concerns, the usage of bio-based goods has increased in recent years. The majority of biologically derived materials have either been made directly from naturally occurring polymers or by first forming bio-based monomers, which are subsequently biochemically polymerised [166]. The hydrolytic breakdown of polymer bonds is known as biopolymer biodegradation. Biodegradable polymers can be grouped based on their specific source ingredients and production methods (Fig. 11). The immediate sources of these materials include the production of biomass (proteins and polysaccharides), synthetic biopolymers derived from biomass such as PLA, petroleum-based products like poly(glycolic acid), polycaprolactone, and poly(butylene succinate-co-adipate), as well as biopolymers produced through fermentation by microorganisms, such as poly(hydroxy alkanoates) and poly(hydroxybutyrate) [167].

5.1. Techniques for producing bio-based materials

A multi-step process is utilized to produce biodegradable packaging components, which includes: (i) breaking down intermolecular bonds, (ii) generating a exceptional molecular composition, and (iii) forming 3D polymer networks through the newly formed linkages. New molecular connections are influenced by the shape (length, breadth, and ratio) of the polymer and processing conditions [168]. Covalent, H-bonding, electrostatic, and hydrophobic interactions create new films. There have been numerous reports on the two fundamental processing methods used to create bio-based plastic polymers: (i) wet processing and (ii) dried processing. The wet process is focused on the type of solvent and how it dissolves, as well as the pH of the solvent, which may have an impact on the creation of polymers. Thermoplastic characteristics of polymers are the focus of dry being processed, where sulfhydryl/disulphide conversion processes are brought on by thermo-mechanical treatment [169]. When creating bio-based polymers from sustainable sources including lipids, carbohydrates, and proteins, wet manufacturing techniques are often used. In wet processing, biopolymer is dissolved in the appropriate solvent in order to generate a film-forming solution. Bioplastic film additions include antimicrobials, micro/nanostructures, cross-linking agents, antioxidant chemicals, plasticising substances, and fillers [170]. Wet processing enhances the mechanical qualities of bioplastic sheets, which benefits the food packaging sector. The drying method makes use of the thermoplastic properties of polymers, which are important in the packaging materials production. The concept of glass transition refers to the temperature at which an amorphous polymer or substance transitions from a rigid, glassy state to a more flexible, semi-solid state. This transition occurs at a specific temperature called the glass transition temperature (Tg). In this process, the molecular mobility of the material increases, allowing the polymer chains to move more freely. In the context of proteins, when they are exposed to heat or other environmental factors, their intermolecular bonds may break, leading to denaturation. During this process, new bonds and linkages may form, altering the material's properties and leading to changes in texture or functionality. Numerous techniques, such as thermal processing and extrusion can be utilized to produce polymer-based encapsulation. Both processes can be applied separately or in combination, with blending and heat processing being employed for the development of the finished product and extrusion for small adjustments [171].

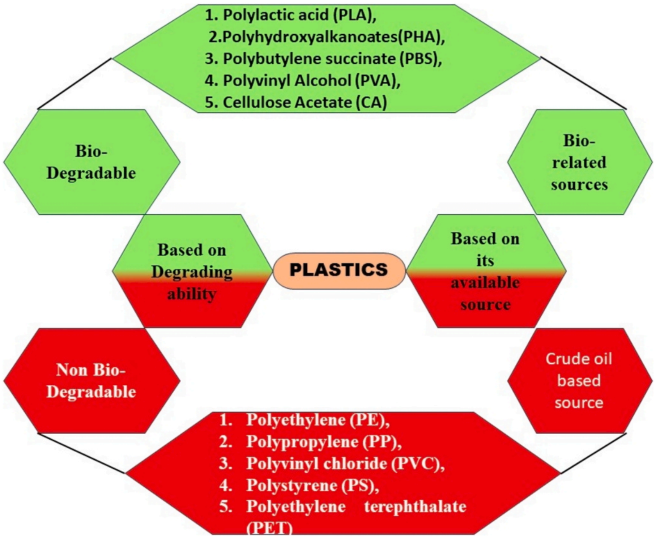

Fig. 11. Classification of bio-based materials on source and degradability.

5.2. Biodegradable polymers and their environmental considerations

Biodegradable polymers are those that can naturally break down into simpler substances such as water, carbon dioxide, and biomass through microbial action over time. The ability to degrade depends on the polymer’s chemical structure, environmental conditions, and the presence of microorganisms. While many biobased polymers possess biodegradability, this is not universally true. For instance, certain forms of polylactic acid (PLA), a biobased polymer, are not easily biodegradable in natural environments like soil or marine ecosystems, even though the polymer itself can be hydrolyzed or enzymatically degraded under controlled conditions in industrial composting environments. This highlights the complexity of biodegradation processes and the need for careful consideration of environmental factors, such as temperature, humidity, and the presence of specific microorganisms, when evaluating the suitability of a polymer for waste management and end-of-life disposal [172,173].

5.3. Biochemical polymerization and its impact on biodegradability

Biochemically polymerized materials are those produced through biochemical processes, involving enzymes, microorganisms, or fermentation instead of traditional chemical polymerization methods. These biopolymers are derived from renewable, biobased feedstocks and are often synthesized through fermentation processes, where microorganisms convert sugars or other organic materials into polymer chains. However, it’s important to note that biochemically polymerized polymers do not automatically correlate with biodegradability or biobased origin. For example, some biochemically polymerized materials can be highly durable and non-biodegradable, while others may be more readily biodegradable. The polymerization process, which uses biological catalysts (enzymes) or living organisms, is distinct from conventional chemical polymerization, but the biodegradability of the resulting polymer depends on its molecular structure and the environmental conditions in which it is disposed. This distinction emphasizes the need for a holistic approach when considering the environmental impacts of biochemically polymerized materials [174,175].

5.4. Eco-friendly alternatives: bio-based plastic packaging materials

Global bio-plastic production is projected to grow from approximately 2.23 million metric tonnes in 2019 to 2.56 million metric tonnes by 2024 was shown in Fig. 12.

Various techniques have been developed to manufacture bio-based materials with diverse characteristics and applications. However, only a limited number of bio-based material families are both biodegradable and derived from renewable biomass. While materials like PCLs and PVAs are produced from non-renewable sources, others, such as PP, PET, polyamide, and bio-based polyethylene, also do not come from renewable resources [177]. The primary methods for producing biodegradable plastics involves directly extracting biopolymers such as cellulose and starch, then by thermo-pressing or molding to create thermoplastic starch polymers, or further functionalizing them to enhance their properties [178–180]. Other processes involved in the production of bio-based plastics include bacterial polyester synthesis, hydrolysis to sugars, fermentation of these sugars into lactic acid, ring-opening lactide condensation/polycondensation to yield PLA, and the chemical conversion of monomers into polymers through polymerization. The lists the several characteristics, such as biological and physiological capabilities, as well as the contribution of additives and nanomaterials to improving the qualities of the bio-based material [181–183].

5.5. Advancing recycling strategies for bio-based materials

Efficient processing methods that transform sorted recovered materials into new products are essential for recycling bio-based materials [184]. Cosate de Andrade et al. (2016) investigated the recycling of PLA and employed life cycle assessment (LCA) to demonstrate that recycling has a smaller environmental footprint than composting [185,186]. During the recycling process, when plastics are subjected to processes such as extrusion or melting, PLA (polylactic acid) may degrade, especially under high temperatures. For biopolyesters to be effectively mechanically recycled, a contaminant-free starting material is essential. Additives incorporated into the bio-polyester layers, such as plasticizers or stabilizers, may cause contamination, hindering the recycling process and affecting the quality of the recycled material. Studies have explored the use of copolymers and cellulose esters as compatibilizers in PLA/cellulose composites and wood/polymer composites to improve the interaction and compatibility between diverse materials. The PLA4-FOOD and BIO4MAP projects examined the recycling of monomaterial PLA through processes like scrap washing, sheet and tray grinding, drying, and palletization using an extrusion machine. According to mechanical and rheological studies, the mechanical properties of the materials and the flowability of the melt are maintained across multiple production cycles.

There are several methods for separating the layers in polymer-based multilayers. PLA is an exceptional choice for environmentally friendly recycling of chemical because it easily hydrolyzes with water to yield lactic acid, which can then be purified and polymerized to recreate high-quality PLA [187].

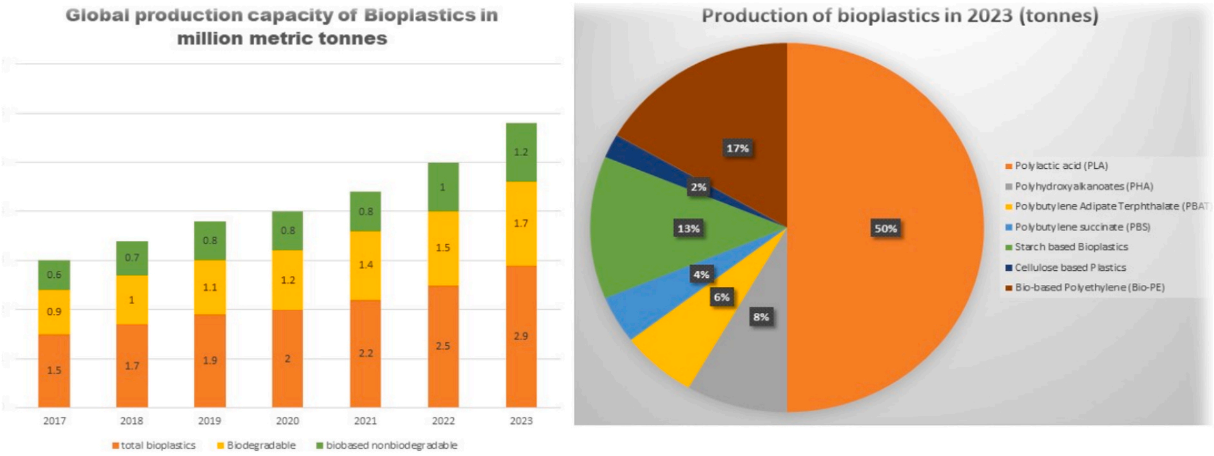

Fig. 12. A) Forecast global production capacities of bioplastics. B) Global production capacities of bioplastics by material type in 2023 [176].

5.6. Challenges in the development and adoption of biobased plastics

At the moment, renewable bio-plastics make up less than 1 % of the 368 million metric tonnes of plastic produced year altogether. Nonetheless, the market for bio-plastics is expanding steadily, and it is anticipated that worldwide production capacity will rise dramatically from 2.42 million tonnes in 2021 to 7.59 million tonnes in 2026 a nearly 200 % increase in the course of five years [188,189]. The growing demand for eco-friendly products is the primary factor driving the increase in bio-plastics development. However, high manufacturing costs, the need for clear and accurate information, and the competitive disadvantage compared to fossil fuel-derived plastics are some of the major challenges facing the growth of bio-plastics. While established plastics made from fossil fuels are subject to fewer laws and expectations, bioplastics, despite having a very modest market share, are frequently criticised for their sustainability and environmental impact [190,191].

6. Life cycle assessment (LCA)

In recognition of their utility and adaptability, multilayer polymers are widely employed in many different industries. However, due to worries about their effects on the environment, Life Cycle Assessments (LCAs) have been developed to assess a system's or product's environmental impact over the course of its whole life cycle, as seen in Fig. 13.

The best layer combinations to improve overall sustainability are found with the aid of life cycle assessments (LCAs). A thorough lifecycle assessment (LCA) was carried out by Koinig et al. (2022) to investigate the environmental effects of monolayer and multilayer films. In order to reduce resource consumption and the potential for global warming, the study underlined the significance of waste management changes, improved film collection, recycling, and improved sorting techniques. The research emphasised the necessity of improving sorting methods and increasing the recycling of single-layer and multilayer films. In order to change waste management into a circular economy, the study stressed the importance of political and societal actions in addition to technological concerns [192]. In 2007, Vidal et al. performed a life cycle assessment (LCA) on PLA-starch-PLA, a biodegradable multilayer polymer composed of carbohydrate polymers. According to the study, its environmental impact is less than that of its counterpart based on petrochemical polymers. Although the biodegradable film performs marginally worse in eutrophication, composting it is thought to have no impact on the carbon dioxide balance. Considering biodegradable materials use less electricity per unit of weight, the LCA also found that their environmental consequences were marginally lower [193]. Pauer et al. (2020) conducted an LCA of six bacon packaging solutions using the open LCA 1.9 software. They discovered that the environmental effects were significantly influenced by the weight of the package and the amount of polyamide. Meat had a 54-fold greater carbon burden than packaging. To cut down on food waste, they recommended giving top priority to product protection [194]. According to a study on hoover bags used in food packaging, the manufacture of PE and PA granules had the biggest negative effects on the environment. A 15 % decrease in overall environmental harm was seen when the researchers looked into ways to use recycled materials and thin the film. The study emphasises how crucial it is to take manufacturing procedures and material composition into account when maximising the environmental performance of multilayer packaging systems [195]. The environmental effects of Tetra Pak and PET bottles, two solutions for juice packing, were

Fig. 13. Life Cycle Assessment of multilayer plastics.

evaluated by Stramarkou et al. in 2021. The creation of packaging and end-of-life situations, including landfilling, incineration, and reuse and recycling, were examined in the study. Tetra Pak outperformed PET bottles in 12 of the 18 impact categories, according to the results of an impact evaluation using GABI software and ReCiPe 2016. Interestingly, the categories of climate change and petroleum depletion showed the most variations. Especially compared to PET bottles, Tetra Pak offers a longer shelf life and is a more environmentally friendly option [196]. The environmental advantages of multilayer packaging vary depending on the circumstances. Designing packaging requires striking a balance between quality and sustainability. Use recyclable resources, optimise layer thickness, and think about polymer combinations to lessen impact. Maintain product quality while maximising recycled content and minimising layer thickness [197]. According to studies, using bioplastics as alternatives to some polymers made from petroleum can drastically cut greenhouse gas emissions. LCAs play a crucial role in identifying the most effective techniques for management and disposal of bioplastic waste. By evaluating the environmental impact of bioplastics at every stage of their life cycle—from raw material extraction to production, use, and disposal—LCAs can provide insights into the sustainability of bioplastics compared to petroleum-based plastics. The application of the Land Use Change (LUC) emissions principle is essential in assessing the full environmental impact of bioplastics, helping to ensure they are a reliable and sustainable alternative to fossil-fuel-derived plastics. To promote sustainability in bioplastics, future studies should focus on individual LCAs for various bioplastic types, assessing their unique environmental footprints. These studies will allow for more tailored approaches to bioplastic development and use, guiding improvements in production processes and waste management.

7. Future challenges of MLP

Fig. 14 illustrates the potential technologies on the horizon for multilayer plastic recycling. However, aspiring researchers face the challenge of broadening these technologies and scaling them up for commercial feasibility. The following challenges and sustainable solutions need to be addressed:

Separation Challenges: Multilayer plastics are composed of multiple layers, often made from different materials, which are difficult to separate efficiently. A major barrier to high recycling rates is the lack of effective sorting and separation technologies. Sustainable solutions are emerging, such as solvent-based techniques, advanced mechanical sorting systems, and enzyme-driven processes that target specific materials for more efficient recycling.

Recycling Infrastructure: The lack of specialized facilities and equipment for processing multilayer materials limits their full recycling potential, as many regions still do not have the required recycling infrastructure specifically for multilayer plastics. One solution is to expand existing recycling infrastructure and integrate multi-layer recycling lines with dedicated machines that can separate and process different plastic combinations. Implementing sustainable recycling technologies such as chemical recycling (e.g., pyrolysis, depolymerization) can help convert multilayer plastics back into high-value chemicals or fuels, reducing reliance on fossil resources.

Economic Viability: The economic feasibility of recycling multilayer plastics remains a concern, as it is often more expensive to recycle than to produce new plastic from virgin materials. To address this, scaling up innovative technologies, enhancing the efficiency of chemical and mechanical recycling, and improving the quality of recycled products is essential. Additionally, promoting circular economy business models, where recycled materials are consistently used in the production of new goods, can help create a more sustainable financial ecosystem for recycling multilayer plastics.

Industry Demand: Government policies, industry demands, and consumer preferences strongly influence the need for recycled multilayer plastics. To stimulate investment in recycling infrastructure and promote sustainable alternatives for packaging, creating a robust market for recycled multilayer plastics is critical. Furthermore, increased use of bio-based plastics, which can be composted or recycled more easily, can support the demand for sustainable alternatives to traditional multilayer plastics.

Research and Development: Overcoming the technical challenges posed by multilayer plastics requires continued innovation in research and development. This includes improvements in chemical recycling technologies, sorting systems, and the development of biodegradable or bio-based alternatives. For example, bio-based polymers, such as polylactic acid (PLA) or polyhydroxyalkanoates (PHA), are being explored as more sustainable alternatives to conventional multilayer plastics. Collaboration between industry stakeholders, including manufacturers, recyclers, legislators, and research institutions, will be crucial in driving

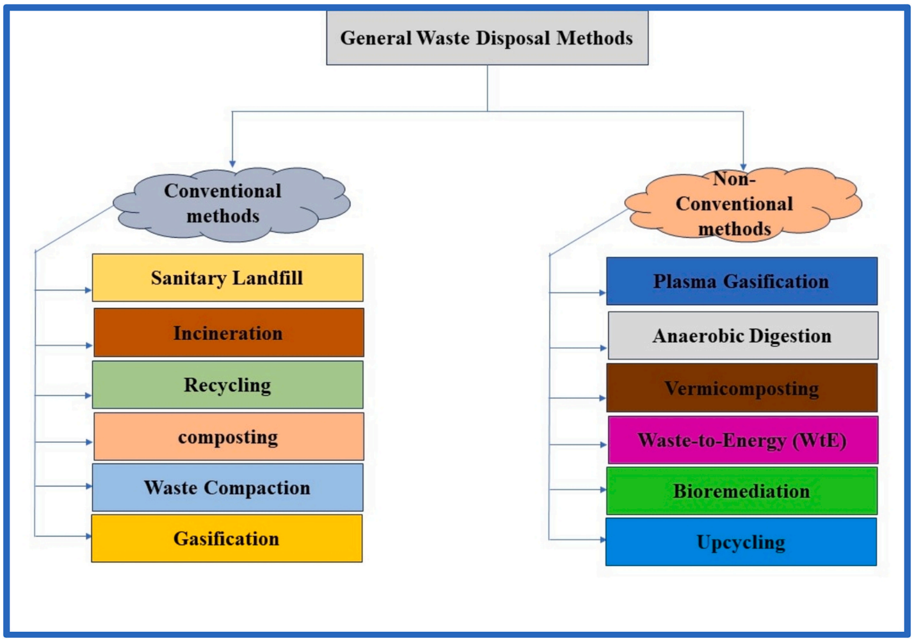

Fig. 14. Emerging technology for post-consumer waste disposal.

progress.

Life Cycle Assessment: It is a comprehensive method for evaluating the environmental impact of products throughout their entire lifecycle. LCA studies on multilayer plastics are essential for identifying key environmental hotspots, from raw material extraction to disposal. Through these studies, more efficient recycling techniques and the use of sustainable bio-based alternatives can be prioritized to minimize environmental impact and energy use.

Supportive Policies: Governments and regulatory bodies have a pivotal role in shaping the future of multilayer plastic recycling and bio-based alternatives. Supportive policies and incentives for sustainable packaging solutions, recycling programs, and extended producer responsibility (EPR) schemes will be essential. Encouraging innovation through tax breaks, subsidies, and clear regulatory frameworks for sustainable plastics can accelerate the adoption of circular economy practices.

Public Awareness and Education: Raising awareness about the environmental impact of multilayer plastics and the importance of recycling is crucial. Educating consumers on the benefits of sustainable packaging options, such as bio-based plastics, and encouraging responsible consumption can help reduce plastic waste. Public involvement through recycling programs, incentivized waste separation, and educational campaigns can drive significant behavioral changes towards more sustainable practices.

Innovations in Bio-based Alternatives: Bio-based plastics, such as PLA, PHA, and bio-based polyethylene, present promising solutions to the sustainability challenges posed by traditional plastics. These materials are derived from renewable resources and offer biodegradability, making them an attractive alternative. However, the success of bio-based plastics depends on ensuring responsible sourcing, sustainable production practices, and the development of efficient recycling methods. Research into biodegradable multilayer plastics, as well as integrating bio-based materials with existing recycling technologies, can lead to a more sustainable future.

Addressing these challenges and incorporating sustainable solutions, such as innovations in recycling and bio-based alternatives, will be key to promoting a circular economy for multilayer plastics. Multilayer plastics sustainable applications are depicted in Fig. 15. By reducing environmental impact and fostering the use of renewable, recyclable, or biodegradable materials, we can create a more sustainable future for packaging and plastic products.

Fig. 15. Multilayer plastics and its sustainable applications.

The growing reliance on non-renewable plastics has led to significant environmental challenges due to inefficient waste management and low recycling rates [Chen et al., 2024]. While mechanical recycling dominates, handling over 90 % of plastic waste, it struggles with material degradation and processing contaminated or mixed plastics. To address these limitations, advanced chemical recycling methods such as pyrolysis, solvolysis, and hydrocracking are being explored as scalable solutions for converting plastic waste into reusable feedstocks. However, optimizing these technologies for energy efficiency, feedstock purity, and large-scale implementation remains a challenge.

Multilayer plastics, widely used in packaging, pose an additional challenge due to poor interfacial adhesion between polymer layers like polyethylene (PE) and polyethylene terephthalate (PET). Rajasekaran and Maji [2018] demonstrated that adding 3 wt% poly(ethylene-co-methacrylic acid) (EMA) compatibilizer to a 3:1 PET-to-PE blend significantly improved tensile strength by 500 %, enabling upcycling into high-performance applications such as automotive components. Efficient separation technologies are also essential for multilayer plastic recycling, and Mumladze et al. [2018] introduced Switchable Hydrophilicity Solvents (SHS), achieving a 99 % separation efficiency in multilayer flexible packaging waste. Unlike conventional solvents, SHS are reversible, reducing chemical waste while recovering high-purity materials for reuse in food-grade packaging and industrial applications.

Emerging recycling technologies, such as photocatalysis, biotechnology, and electrochemistry, offer promising alternatives for plastic waste management. Photocatalysis enables light-driven plastic degradation, reducing thermal energy requirements, while biotechnological approaches, including enzymatic depolymerization, have shown effectiveness in breaking down PET and polyurethane at lower temperatures. Electrochemical methods present another innovative strategy, providing selective plastic breakdown while generating value-added products. Although these technologies are still in early research phases, their potential for large-scale implementation could contribute significantly to a sustainable circular economy.

8. Conclusion

Effective collection systems and targeted recycling initiatives are essential for ensuring that multilayer plastics are properly separated at the waste source, preventing their incineration or landfill disposal. Once sorted, these plastics can be recycled through various methods, including mechanical and chemical recycling. Mechanical recycling typically involves shredding, cleaning, and melting plastics to produce flakes or pellets that can be reused in new products. Meanwhile, efforts to optimize pyrolysis, through improved catalysts and refined process conditions, are enhancing both the yield and quality of the products derived from multilayer polymers. Chemical recycling, which holds great potential, can convert multilayer plastics into valuable chemicals or fuels, helping to reduce environmental impacts and reliance on fossil fuels by regenerating raw materials from complex molecular structures. In the case of PET recycling, processes like hydrolysis, glycolysis (producing BHET), and aminolysis facilitate depolymerization, while methanolysis, using methanol as a solvent, generates EG and DMT. Additionally, catalytic depolymerization of hydrocarbon monomers supports a circular economy. To improve the efficiency of separating the layers in multilayer plastics, researchers and recycling companies are exploring advanced solvent-based separation technologies. However, challenges such as the economic viability of recycling multilayer plastics and the scalability of these technologies remain. The scientific community continues to make progress toward overcoming these obstacles. In addition to recycling, bio-based plastics offer a promising solution to the sustainability challenges posed by conventional plastics. However, their long-term sustainability hinges on ethical sourcing, sustainable manufacturing practices, and consistent production growth. This review underscores both sustainable recycling approaches for multilayer plastics and the development of bio-based alternatives.

CRediT authorship contribution statement

Maha Awjan Alreshidi: Writing – review & editing. **Krishna Kumar Yadav:** Resources. **G. Shoba:** Supervision, Formal analysis. **Amel Gacem:** Visualization, Methodology. **S. Padmanabhan:** Methodology, Project administration. **T. Vinod Kumar:** Writing – original draft, Visualization. **Ahmed M. Fallatah:** Data curation, Conceptualization. **Javed Khan Bhutto:** Visualization, Resources. **Fahad M. Aldosari:** Visualization, Validation, Investigation. **Manawwer Alam:** Data curation, Conceptualization. **Muhammad A. Abo El-Khair:** Project administration, Methodology. **P. Tamizhdurai:** Methodology, Project administration. **A. Subramani:** Investigation, Formal analysis. **V.L. Mangesh:** Data curation, Formal analysis. **R. Kumaran:** Formal analysis.

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.

Acknowledgement

The authors extend their appreciation to the Deanship of Research and Graduate Studies at King Khalid University for funding this work through Large Research Project under grant number RGP 2/64/46.

Data availability

The authors do not have permission to share data.

References

[1] A.L. Allison, H.M. Baird, F. Lorencatto, T.L. Webb, S. Michie, Reducing plastic waste: A meta-analysis of influences on behaviour and interventions, J. Clean. Prod. 20 (380) (2022 Dec) 134860.

[2] X. Ma, C. Park, J. Moultrie, Factors for eliminating plastic in packaging: The European FMCG experts' view, J. Clean. Prod. 20 (256) (2020 May) 120492.

[3] G.R. Mong, H. Tan, D.D. Sheng, H.Y. Kek, B.B. Nyakuma, K.S. Woon, M. H. Othman, H.S. Kang, P.S. Goh, K.Y. Wong, A review on plastic waste valorisation to advanced materials: Solutions and technologies to curb plastic waste pollution, J. Clean. Prod. 13 (2023 Dec) 140180.

[4] S.K. Shin, N. Um, Y.J. Kim, N.H. Cho, T.W. Jeon, New policy framework with plastic waste control plan for effective plastic waste management, Sustainability. 12 (2020) 6049.

[5] Q. Ding, H. Zhu, The key to solving plastic packaging wastes: Design for recycling and recycling technology, Polymers 15 (6) (2023) 1485.

[6] Organisation for Economic C-o, Development. Global Plastics Outlook: Policy Scenarios to 2060: OECD Publishing; 2022.

[7] A.A. Phelan, K. Meissner, J. Humphrey, H. Ross, Plastic pollution and packaging: Corporate commitments and actions from the food and beverage sector, J. Clean. Prod. 10 (331) (2022 Jan) 129827.

[8] X. Zhang, Y. Xu, X. Zhang, H. Wu, J. Shen, R. Chen, et al., Progress on the layer-by-layer assembly of multilayered polymer composites: Strategy, structural control and applications, Prog. Polym. Sci. 89 (2019) 76–107.

[9] R. Shemesh, M. Krepker, D. Goldman, Y. Danin-Poleg, Y. Kashi, N. Nitzan, et al., Antibacterial and antifungal LDPE films for active packaging, Polym. Adv. Technol. 26 (2015) 110–116.

[10] M. Gumiero, D. Peressini, A. Pizzariello, A. Sensidoni, L. Iacumin, G. Comi, et al., Effect of TiO2 photocatalytic activity in a HDPE-based food packaging on the structural and microbiological stability of a short-ripened cheese, Food Chem. 138 (2013) 1633–1640.

[11] T.S. Gomes, L.L.Y. Visconte, E.B.A.V. Pacheco, Life cycle assessment of polyethylene terephthalate packaging: an overview, J. Polym. Environ. 27 (2019) 533–548.

[12] S. Nayak, S. kumar Khuntia, Development and study of properties of Moringa oleifera fruit fibers/polyethylene terephthalate composites for packaging applications, Compos. Commun. 15 (2019) 113–119.

[13] M. Mulla, J. Ahmed, H. Al-Attar, E. Castro-Aguirre, Y.A. Arfat, R. Auras, Antimicrobial efficacy of clove essential oil infused into chemically modified LLDPE film for chicken meat packaging, Food Control 73 (2017) 663–671.

[14] E. Häsänen, Composition analysis and compatibilization of post-consumer recycled multilayer plastic films, 2016.

[15] K. Plevová, M. Feuchter, M. Wellacher, A. Jamnik, N. Wild, H. Pichorner, et al., Closed-loop recycling of packaging waste at the food manufacturer Freiberger, Chair of Materials Science and Testing of Polymers, 210.

[16] F. Hafsa, K.J. Dooley, G. Basile, R. Buch, A typology and assessment of innovations for circular plastic packaging, J. Clean. Prod. 1 (369) (2022 Oct) 133313.

[17] T.I. Butler, B.A. Morris, PE-based multilayer film structures, in: multilayer flex. Packag. Second Ed., 2016: pp. 281–310. https://doi.org/10.1016/B978-0-323-37100-1.00017-X.

[18] C.T.de M. Soares, M. Ek, E. Östmark, M. Gällstedt, S. Karlsson, Recycling of multi-material multilayer plastic packaging: current trends and future scenarios, Resour. Conserv. Recycl., 105905 (2022) 176, https://doi.org/10.1016/J.RESCONREC.2021.105905.

[19] G. Cabrera, J. Li, A. Maazouz, K. Lamnawar, A Journey from Processing to Recycling of Multilayer Waste Films: a Review of Main Challenges and Prospects, Polymers (Basel) 14 (2022), https://doi.org/10.3390/polym14122319.

[20] T.W. Walker, N. Frelka, Z. Shen, A.K. Chew, J. Banick, S. Grey, M.S. Kim, J. A. Dumesic, R.C. Van Lehn, G.W. Huber, Recycling of multilayer plastic packaging materials by solvent-targeted recovery and precipitation, Sci. Adv., 6 (2020) 1, https://doi.org/10.1126/sciadv.aba7599.

[21] J.P. Lange, Managing plastic waste─ sorting, recycling, disposal, and product redesign, ACS Sustain. Chem. Eng. 9 (47) (2021 Nov 12) 15722–15738.

[22] S. King, K.E. Locock, A circular economy framework for plastics: A semi-systematic review, J. Clean. Prod. 1 (364) (2022 Sep) 132503.

[23] Q. Liu, S. Martinez-Villarreal, S. Wang, N.N.T. Tien, M. Kammoun, Q. De Roover, et al., The role of plastic chemical recycling processes in a circular economy context, Chem. Eng. J. 498 (2024) 155227, https://doi.org/10.1016/j.cej.2024.155227.

[24] J. Saleem, Z.K.B. Moghal, R. Luque, G. McKay, Towards green membranes: Repurposing waste polypropylene with a single plant-based solvent via tandem spin-casting and annealing, Chem. Eng. J. 481 (2024) 148560, https://doi.org/10.1016/j.cej.2024.148560.

[25] T. Mumladze, S. Yousef, M. Tatariants, R. Kriūkienė, V. Makarevicius, S. I. Lukošiūtė, et al., Sustainable approach to recycling of multilayer flexible packaging using switchable hydrophilicity solvents, Green Chem. 20 (15) (2018) 3604–3618, https://doi.org/10.1039/C8GC01062E.

[26] S. Chen, Y.H. Hu, Advancements and future directions in waste plastics recycling: From mechanical methods to innovative chemical processes, Chem. Eng. J. 493 (2024) 152727, https://doi.org/10.1016/j.cej.2024.152727.

[27] D. Rajasekaran, P.K. Maji, Recycling of plastic wastes with poly(ethylene-co-methacrylic acid) copolymer as compatibilizer and their conversion into high-end product, Waste Manag. 74 (2018) 135–143, https://doi.org/10.1016/j.wasman.2018.01.018.

[28] J.G. Rosenboom, R. Langer, G. Traverso, Bioplastics for a circular economy, Nat. Rev. Mater. 7 (2022) 117–137, https://doi.org/10.1038/s41578-021-00407-8.

[29] L. Delva, C. Deceur, N. Van Damme, K. Ragaert, Compatibilization of PET-PE blends for the recycling of multilayer packaging foils. 1 ed: AIP Publishing LLC. p. 030005.

[30] (a) B.A. Morris, The science and technology of flexible packaging: multilayer films from resin and process to end use: William Andrew; 2022. (b) S. Mooninta, S. Poompradub, P. Prasassarakich, Packaging film of PP/LDPE/PLA/clay composite: physical, barrier and degradable properties, J. Polym. Environ. 2020; 28:3116-28.

[31] A.C.C. de Leon, Í.G.M. da Silva, K.D. Pangilinan, Q. Chen, E.B. Caldona, R. C. Advincula, High performance polymers for oil and gas applications, React. Funct. Polym. 162 (2021) 104878, https://doi.org/10.1016/j.reactfunctpolym.2021.104878.

[32] Patent Cooperation Treaty. (2008). WO2008138133A1: Title of the patent. https://patents.google.com/patent/WO2008138133A1/en.

[33] A. Felgel-Farnholz, A. Schweighuber, C.W. Klampfl, J. Fischer, Comparative study on the degradation of HDPE, LLDPE, and LDPE during multiple extrusions, Polym. Degrad. Stab. 216 (2023) 110486, https://doi.org/10.1016/j.polymdegradstab.2023.110486.

[34] Americorp International. Understanding HDPE, LLDPE, LDPE, PP, PVC, PS, PET, and EVA. Americorp International. Retrieved March 1, 2025, from https://americorpint.com/understanding-hdpe-lldpe-ldpe-pp-pvc-ps-pet-and-eva/.

[35] O.Y. Alothman, Processing and characterization of high-density polyethylene/ethylene vinyl acetate blends with different VA contents, Adv. Mater. Sci. Eng. 2012 (2012) 635693, https://doi.org/10.1155/2012/635693.

[36] C.M.A. Lopes, M.I. Felisberti, Composite of low-density polyethylene and aluminum obtained from the recycling of postconsumer aseptic packaging, J. Appl. Polym. Sci. 101 (5) (2006) 3183–3191, https://doi.org/10.1002/app.23406.

[37] S.C. Chen, L.H. Zhang, G. Zhang, G.C. Zhong, J. Li, X.M. Zhang, et al., An investigation and comparison of the blending of LDPE and PP with different intrinsic viscosities of PET, Polymers (Basel). 10 (2) (2018) 147, https://doi.org/10.3390/polym10020147.

[38] T.I. Butler, B.A. Morris, PE-based multilayer film structures, in: J.R. Wagner (Ed.), Multilayer Flexible Packaging, 2nd ed., William Andrew Publishing, 2016, pp. 281–310, 10.1016/B978-0-323-37100-1.00017-X.

[39] Omnexus SpecialChem. HDPE, LDPE, LLDPE comparison [Internet]. [cited 2025 Mar 5]. Available from: https://omnexus.specialchem.com/plastics-and-elastomers/polyethylene-pe/hdpe-ldpe-lldpe-comparison.

[40] D. Langhe, M. Ponting, Manufacturing and novel applications of multilayer polymer films, William Andrew (2016).

[41] W. Zhang, J.-W. Rhim, Titanium dioxide (TiO2) for the manufacture of multifunctional active food packaging films, Food Packag. Shelf Life 31 (2022) 100806.

[42] J. Wang, D.J. Gardner, N.M. Stark, D.W. Bousfield, M. Tajvidi, Z. Cai, Moisture and oxygen barrier properties of cellulose nanomaterial-based films, ACS Sustain. Chem. Eng. 6 (1) (2018) 49–70, https://doi.org/10.1021/acssuschemeng.7b03523.

[43] B. Bamps, M. Buntinx, R. Peeters, Seal materials in flexible plastic food packaging: A review, Packag. Technol. Sci. 36 (7) (2023) 507–532, https://doi.org/10.1002/pts.2732.

[44] J. Schmidt, L. Grau, M. Auer, R. Maletz, J. Woidasky, Multilayer packaging in a circular economy, Polymers 14 (9) (2022 Apr 29) 1825.

[45] M.A. Anwar, S. Suprihatin, N.A. Najib, M., B. Pranoto, Challenges and prospects of multilayer plastic waste management in several countries: A systematic literature review, Case Stud. Chem. Environ. Eng. 10 (2024) 100911, https://doi.org/10.1016/j.cscee.2024.100911.

[46] T. Anukiruthika, P. Sethupathy, A. Wilson, K. Kashampur, J.A. Moses, C. Anandharamakrishnan, Multilayer packaging: Advances in preparation techniques and emerging food applications, Compr. Rev. Food Sci. Food Saf. 19 (2020) 1156–1186.

[47] M. Ščetar, Multilayer Packaging Materials, Pharmaceuticals and Cosmetics, Packaging Materials and Processing for Food, 2021, pp. 131–144.

[48] Y. Wu, X. Gao, J. Wu, T. Zhou, T.T. Nguyen, Y. Wang, Biodegradable polylactic acid and its composites: characteristics, processing, and sustainable applications in sports, Polymers 15 (14) (2023) 3096, https://doi.org/10.3390/polym15143096.

[49] P. Grassl, Monomaterial packaging: A solution to the global plastics crisis, ONdrugDelivery. 2018 (2018) 87–89.

[50] O.H. Fred-Ahmadu, G. Bhagwat, I. Oluyoye, N.U. Benson, O.O. Ayejuyo, T. Palanisami, Interaction of chemical contaminants with microplastics: principles and perspectives, Sci. Total Environ. 706 (2020) 135978.

[51] M. Olejnik, Nanokompozyty polimerowe z udziałem montmorylonitu—Otrzymywanie, metody oceny, właściwości i zastosowanie, Tech Wyrob Włókiennicze. 5 (2008) 67–74.

[52] M. Tolinski, Colorants, in: M. Tolinski (Ed.), Additives for Polyolefins, 2nd ed., William Andrew Publishing, 2015, pp. 103–116, 10.1016/B978-0-323-35884-2.00009-0.

[53] K.C. Omidoyin, E.H. Jho, Environmental occurrence and ecotoxicological risks of plastic leachates in aquatic and terrestrial environments, Sci. Total Environ. 954 (2024) 176728, https://doi.org/10.1016/j.scitotenv.2024.176728.

[54] V. Marturano, P. Cerruti, V. Ambrogi, Polymer additives, Phys. Sci. Rev. 2 (6) (2017) 20160130, https://doi.org/10.1515/psr-2016-0130.

[55] L. Andeobu, S. Wibowo, S. Grandhi, Informal e-waste recycling practices and environmental pollution in Africa: What is the way forward? Int. J. Hyg. Environ. Health 252 (2023) 114192 https://doi.org/10.1016/j.ijheh.2023.114192.

[56] S. Biedermann-Brem, M. Biedermann, S. Pfenninger, K. Grob, Plasticizers in PVC toys and childcare products: What succeeds the phthalates? Market survey 2007, Chromatographia 68 (2008) 227–234, https://doi.org/10.1365/s10337-008-0672-9.

[57] C. DeArmitt, R. Rothon, Dispersants and coupling agents, in: M. Kutz (Ed.), Applied Plastics Engineering Handbook, 2nd ed., William Andrew Publishing, 2017, pp. 501–516, https://doi.org/10.1016/B978-0-323-39040-8.00022-5.

[58] M. Wakabayashi, T. Kohno, Y. Tanaka, T. Kanai, Study on the bleeding mechanism of slip agents in a polypropylene film using molecular dynamics, Int. Polym. Proc. 24 (2009) 133–139.

[59] G. Wypych, Handbook of antiblocking, release, and slip additives, Elsevier (2021).

[60] J. Heo, M. Choi, J. Hong, Facile surface modification of polyethylene film via spray-assisted layer-by-layer self-assembly of graphene oxide for oxygen barrier properties, Sci. Rep. 9 (1) (2019) 2754.

[61] H. Arnon-Rips, E. Poverenov, Improving food products' quality and storability by using Layer by Layer edible coatings, Trends Food Sci. Technol. 75 (2018) 81–92.

[62] L. Zhao, G. Duan, G. Zhang, H. Yang, S. He, S. Jiang, Electrospun functional materials toward food packaging applications: A review, Nanomaterials 10 (2020) 150.

[63] Y. Hirayama, T. Yamada, Y. Sawa, Multilayered preform and multilayered stretch-blow-formed container, Google Patents (2018).

[64] A.G. Azevedo, C. Barros, S. Miranda, A.V. Machado, O. Castro, B. Silva, et al., Active flexible films for food packaging: a review, Polymers 14 (2022) 2442.

[65] B. Hassan, S.A.S. Chatha, A.I. Hussain, K.M. Zia, N. Akhtar, Recent advances on polysaccharides, lipids and protein based edible films and coatings: A review, Int. J. Biol. Macromol. 109 (2018) 1095–1107.

[66] J. Jeong, J. Choi, Development of AOP relevant to microplastics based on toxicity mechanisms of chemical additives using ToxCast™ and deep learning models combined approach, Environ. Int. 137 (2020) 105557.

[67] J.P. da Costa, A. Avellan, C. Mouneyrac, A. Duarte, T. Rocha-Santos, Plastic additives and microplastics as emerging contaminants: Mechanisms and analytical assessment, TrAC Trends in Analytical Chemistry. 2022:116898.

[68] S.J. Calva-Estrada, M. Jiménez-Fernández, E. Lugo-Cervantes, Protein-based films: Advances in the development of biomaterials applicable to food packaging, Food Eng. Rev. 11 (2019) 78–92.

[69] J.A. Bhushani, C. Anandharamakrishnan, Electrospinning and electrospraying techniques: Potential food based applications, Trends Food Sci. Technol. 38 (2014) 21–33.

[70] M. Świetlicki, D. Chocyk, T. Klepka, A. Prószyński, A. Kwaśniewska, J. Borc, et al., The structure and mechanical properties of the surface layer of polypropylene polymers with talc additions, Materials 13 (2020) 698.

[71] D. Dziadowiec, D. Matykiewicz, M. Szostak, J. Andrzejewski, Overview of the cast polyolefin film extrusion technology for multi-layer packaging applications, Materials. 16 (2023) 1071.

[72] J. Vartiainen, Y. Shen, T. Kaljunen, T. Malm, M. Vähä-Nissi, M. Putkonen, et al., Bio-based multilayer barrier films by extrusion, dispersion coating and atomic layer deposition, J. Appl. Polym. Sci. 133 (2015).

[73] J.R. Wagner Jr, Multilayer flexible packaging, William Andrew (2016).

[74] A.R. Ajitha, M.K. Aswathi, H.J. Maria, J. Izdebska, S. Thomas, Multilayer Polymer Films. Multicomponent Polymeric Materials. (2016) 229–258.

[75] X. Zhang, H. Chen, H. Zhang, Layer-by-layer assembly: from conventional to unconventional methods, Chem. Commun. 1395–405 (2007).

[76] D.H. Reneker, A.L. Yarin, Electrospinning jets and polymer nanofibers, Polymer 49 (2008) 2387–2425.

[77] International Organization for Standardization. Plastics—Guidelines for the recovery and recycling of plastics waste. ISO 15270:2008 [Internet]. 2008 [cited 2025 Mar 5]. Available from: https://www.iso.org/standard/45089.html.

[78] U.S. Food and Drug Administration, Guidance for Industry: Use of Recycled Plastics in Food Packaging, FDA [Internet]. 2021 [cited 2025 Mar 5]. Available from: https://www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-industry-use-recycled-plastics-food-packaging-chemistry-considerations.

[79] J. Hopewell, R. Dvorak, E. Kosior, Plastics recycling: Challenges and opportunities, Philos. Trans. R. Soc. B Biol. Sci. 364 (1526) (2009) 2115–2126, https://doi.org/10.1098/rstb.2008.0311.

[80] J. Yang, Y.P. Xu, P. Chen, J.Y. Li, D. Liu, X.L. Chu, Combining spectroscopy and machine learning for rapid identification of plastic waste: Recent developments and future prospects, J. Clean. Prod. 15 (2023 Nov) 139771.

[81] K. Kaiser, M. Schmid, M. Schlummer, Recycling of polymer-based multilayer packaging: A review, Recycling 3 (1) (2017) 1.

[82] J.M. Soto, G. Blázquez, M. Calero, L. Quesada, V. Godoy, M.Á. Martín-Lara, A real case study of mechanical recycling as an alternative for managing of polyethylene plastic film presented in mixed municipal solid waste, J. Clean. Prod. 1 (203) (2018 Dec) 777–787.

[83] Z.O.G. Schyns, M.P. Shaver, Mechanical recycling of packaging plastics: A review, Macromol. Rapid Commun. 42 (2021) 2000415.

[84] M.A. Martín-Lara, J.A. Moreno, G. Garcia-Garcia, S. Arjandas, M. Calero, Life cycle assessment of mechanical recycling of post-consumer polyethylene flexible films based on a real case in Spain, J. Clean. Prod. 10 (365) (2022 Sep) 132625.

[85] B.B. Turriziani, R.P. Vieira, L. Marangoni Júnior, R.M.V. Alves, Mechanical recycling of multilayer flexible packaging employing maleic anhydride as compatibilizer, J. Polym. Environ. (2023) 1–13.

[86] K. Sun, F. Li, J. Li, J. Li, C. Zhang, S. Chen, X. Sun, J. Cui, Optimisation of compatibility for improving elongation at break of chitosan/starch films, RSC Adv. 9 (41) (2019) 24451–24459, https://doi.org/10.1039/C9RA04893C.

[87] K. Kaiser, M. Schmid, M. Schlummer, Recycling of polymer-based multilayer packaging: a review, Recycling. (2018).

[88] G.A. Uehara, M.P. França, S.V. Canevarolo Junior, Recycling assessment of multilayer flexible packaging films using design of experiments, Polímeros 25 (2015) 371–381.

[89] S.C. Kosloski-Oh, Z.A. Wood, Y. Manjarrez, J.P. de Los Rios, M.E. Fieser, Catalytic methods for chemical recycling or upcycling of commercial polymers, Mater. Horiz. 8 (4) (2021) 1084–1129.

[90] S. Conroy, X. Zhang, Theoretical insights into chemical recycling of polyethylene terephthalate (PET), Polym. Degrad. Stab. 223 (2024) 110729, https://doi.org/10.1016/j.polymdegradstab.2024.110729.

[91] J. Huang, A. Veksha, W.P. Chan, A. Giannis, G. Lisak, Chemical recycling of plastic waste for sustainable material management: A prospective review on catalysts and processes, Renew. Sust. Energ Rev. 154 (2022) 111866, https://doi.org/10.1016/j.rser.2021.111866.

[92] L. Zhang, J. Gao, J. Zou, F. Yi, Hydrolysis of poly(ethylene terephthalate) waste bottles in the presence of dual functional phase transfer catalysts, J. Appl. Polym. Sci. 130 (2013) 2790–2795, https://doi.org/10.1002/app.39497.

[93] S.R. Shukla, A.M. Harad, Aminolysis of polyethylene terephthalate waste, Polym. Degrad. Stab. 91 (8) (2006) 1850–1854, https://doi.org/10.1016/j.polymdegradstab.2005.11.005.

[94] L. Zhou, E. Qin, H. Huang, Y. Wang, M. Li, PET glycolysis to BHET efficiently catalyzed by stable and recyclable Pd-Cu/γ-Al_2O_3, Molecules (Basel). 29 (18) (2024) 4305, https://doi.org/10.3390/molecules29184305.

[95] A.B. Lende, S. Bhattacharjee, C.S. Tan, Hydrogenation of polyethylene terephthalate to environmentally friendly polyester over Vulcan XC-72 carbon supported Rh-Pt bimetallic catalyst, Catal. Today 388–9 (2022) 117–124, https://doi.org/10.1016/j.cattod.2020.09.013.

[96] T. Chen, T. Cai, Q. Jin, J. Ji, Design and fabrication of functional polycaprolactone, E-Polymers 15 (1) (2015) 3–13, https://doi.org/10.1515/epoly-2014-0158.

[97] A.A. Tereshchenko, I.K. Goncharova, A.D. Zagrebaev, S.V. Chapek, I. O. Nechitailova, D.Y. Molodtsov, et al., Heterophase Pt/EG-catalyzed hydrosilylation in droplet microfluidics: Spectral monitoring and efficient 3D-printed reactors, Chem. Eng. J. 498 (2024) 155016, https://doi.org/10.1016/j.cej.2024.155016.

[98] R.Y. Lukin, A.M. Kuchkaev, A.V. Sukhov, G.E. Bekmukhamedov, D.G. Yakhvarov, Platinum-catalyzed hydrosilylation in polymer chemistry, Polymers (Basel). 12 (10) (2020) 2174, https://doi.org/10.3390/polym12102174.

[99] J.O.C. de França, V.D. da Silva, M.F. Paiva, S.C.L. Dias, J.A. Dias, Polymers based on PLA from synthesis using D,L-lactic acid (or racemic lactide) and some biomedical applications: a short review, Polymers (Basel). 14 (12) (2022) 2317, https://doi.org/10.3390/polym14122317.

[100] R.J. Hofmann, M. Vlatković, F. Wiesbrock, Fifty years of hydrosilylation in polymer science: a review of current trends of low-cost transition-metal and metal-free catalysts, non-thermally triggered hydrosilylation reactions, and industrial applications, Polymers (Basel). 9 (10) (2017) 534, https://doi.org/10.3390/polym9100534.

[101] M.Z. Siddiqui, Y.K. Park, Y. Kang, A. Watanabe, S. Kim, Y.M. Kim, Effective use of aluminum-plastic laminate as a feedstock for catalytic pyrolysis over micro and mesoporous catalysts, J. Clean. Prod. 229 (2019) 1093–1101, https://doi.org/10.1016/j.jclepro.2019.04.404.

[102] J. Wang, Y. Zhu, Y. Fu, Abrasion resistance of biaxially oriented polypropylene films coated with nanocomposite hard coatings, Appl. Surf. Sci. 285 (Pt B) (2013) 697–701, https://doi.org/10.1016/j.apsusc.2013.08.112.

[103] K. Sivagami, G. Divyapriya, R. Selvaraj, P. Madhiyazhagan, N. Sriram, I. Nambi, Catalytic pyrolysis of polyolefin and multilayer packaging-based waste plastics: A pilot scale study, Process Saf. Environ. Prot. 149 (2021) 497–506, https://doi.org/10.1016/j.psep.2020.10.038.

[104] G. Cabrera, J. Li, A. Maazouz, K. Lamnawar, A journey from processing to recycling of multilayer waste films: a review of main challenges and prospects, Polymers 14 (2022) 2319.

[105] A. Maeurer, M. Schlummer, O. Beck, U.S. Patent No. 8,138,232. Washington, DC: U.S. Patent and Trademark Office, 2012.

[106] W. Linder, A. Thiele, G. Gorski, Method for obtaining ldpe from used plastic films, EP20020742797 (2004).

[107] J. Kubiczek, W. Derej, B. Hadasik, A. Matuszewska, Chemical recycling of plastic waste as a mean to implement the circular economy model in the European Union, J. Clean. Prod. 20 (406) (2023 Jun) 136951.

[108] C. Samorì, D. Cespi, P. Blair, P. Galletti, D. Malferrari, F. Passarini, E. Tagliavini, Application of switchable hydrophilicity solvents for recycling multilayer packaging materials, Green Chem. 19 (7) (2017) 1714–1720.

[109] K. Phan, S. Ügdüler, L. Harinck, R. Denolf, M. Roosen, G. O'Rourke, S. De Meester, Analysing the potential of the selective dissolution of elastane from mixed fiber textile waste, Resour. Conserv. Recycl. 191 (2023) 106903.

[110] J. Cavalcante, R. Hardian, G. Szekely, Antipathogenic upcycling of face mask waste into separation materials using green solvents, Sustain. Mater. Technol. 32 (2022) e00448.

[111] M. Ramírez-Martínez, S.L. Aristizábal, G. Szekely, S.P. Nunes, Bio-based solvents for polyolefin dissolution and membrane fabrication: from plastic waste to value-added materials, Green Chem. 25 (3) (2023) 966–977.

[112] Mukhopadhyay, Ashutosh. "Process of de-lamination of multi-layer laminated packaging industrial refuse." U.S. Patent Application 10/450,699, filed March 18, 2004.

[113] K.M. Patel, M.M. Vaviya, M.H. Patel, Process for Recovering Low-Density Polyethylene from Flexible Packaging Material, WO15159301 A3, 21 January 2016.

[114] A.K. Kulkarni, S. Daneshvarhosseini, H. Yoshida, Effective recovery of pure aluminum from waste composite laminates by sub- and super-critical water, J. Supercrit. Fluids 55 (2011) 992–997.

[115] Y.C. Lee, M.J. Kim, H.C. Lee, A Recycling Method of Multilayer Packaging Film Waste. EP1683829 A1, 26 July 2006.

[116] K. Benzing, J. Fleig, D. Feiss, H. Rott, Separating Aluminum-Containing Composites, E.g. For Recycling Packaging Materials, Involves Treatment with Alkali Solution to Dissolve Aluminum and Precipitate Other Materials. DE10102554 A1, 25 July 2002.

[117] M. Vagnoni, W. Pitacco, V. Arpaia, E. Catelli, C. Gualandi, R. Mastroddi, P. Galletti, Recycling of multilayer packaging waste with switchable anionic surfactants, Resour. Conserv. Recycl. 198 (2023) 107141.

[118] D. Stanica-Ezeanu, D. Matei, Natural depolymerization of waste poly (ethylene terephthalate) by neutral hydrolysis in marine water, Sci. Rep. 11 (1) (2021 Feb 24) 4431.

[119] M. Čolnik, Ž. Knez, M. Škerget, Sub-and supercritical water for chemical recycling of polyethylene terephthalate waste, Chem. Eng. Sci. 233 (2021) 116389.

[120] K. Chan, A. Zinchenko, Design and synthesis of functional materials by chemical recycling of waste polyethylene terephthalate (PET): Opportunities and challenges, J. Clean. Prod. 20 (2023 Nov) 139828.

[121] M.A. Haque, K. Candlen, A.M. Peterson, J.A. Ratto, W.T. Chen, Degradation behavior of multilayer packaging films in the presence of a highly acidic sauce, J. Food Eng. 340 (2023) 111318.

[122] P. McKeown, M. Kamran, M.G. Davidson, M.D. Jones, L.A. Román-Ramírez, J. Wood, Organocatalysis for versatile polymer degradation, Green Chem. 22 (2020) 3721–3726.

[123] P. Fang, B. Liu, J. Xu, Q. Zhou, S. Zhang, J. Ma, High-efficiency glycolysis of poly (ethylene terephthalate) by sandwich-structure polyoxometalate catalyst with two active sites, Polym. Degrad. Stab. 1 (156) (2018 Oct) 22–31.

[124] I. Cano, C. Martin, J.A. Fernandes, R.W. Lodge, J. Dupont, F.A. Casado-Carmona, et al., Paramagnetic ionic liquid-coated SiO2@ Fe3O4 nanoparticles—The next generation of magnetically recoverable nanocatalysts applied in the glycolysis of PET, Appl. Catal. B 260 (2020) 118110.

[125] V.S. Palekar, R.V. Shah, S.R. Shukla, Ionic liquid-catalyzed aminolysis of poly (ethylene terephthalate) waste, J. Appl. Polym. Sci. 126 (3) (2012 Nov 5) 1174–1181.

[126] Y.S. Parab, N.D. Pingale, S.R. Shukla, Aminolytic depolymerization of poly (ethylene terephthalate) bottle waste by conventional and microwave irradiation heating, J. Appl. Polym. Sci. 125 (2) (2012 Jul 15) 1103–1107.

[127] J. Demarteau, I. Olazabal, C. Jehanno, H. Sardon, Aminolytic upcycling of poly (ethylene terephthalate) wastes using a thermally-stable organocatalyst, Polym. Chem. 11 (2020) 4875–4882.

[128] D.D. Pham, J. Cho, Low-energy catalytic methanolysis of poly (ethyleneterephthalate), Green Chem. 23 (1) (2021) 511–525.

[129] T.H. Myren, T.A. Stinson, Z.J. Mast, C.G. Huntzinger, O.R. Luca, Chemical and electrochemical recycling of end-use poly (ethylene terephthalate)(PET) plastics in batch, microwave and electrochemical reactors, Molecules 25 (12) (2020 Jun 13) 2742.

[130] Y. Zhang, H. Jiang, Y. Du, C. Wang, H. Wang, Surface alcoholysis induced by alkali-activation ethanol: A novel scheme for binary flotation of polyethylene terephthalate from other plastics, J. Clean. Prod. 10 (314) (2021 Sep) 128096.

[131] S. Marullo, C. Rizzo, N.T. Dintcheva, F. D'Anna, Amino acid-based cholinium ionic liquids as sustainable catalysts for PET depolymerization, ACS Sustain. Chem. Eng. 9 (45) (2021) 15157–15165.

[132] J. Payne, M.D. Jones, The chemical recycling of polyesters for a circular plastics economy: challenges and emerging opportunities, ChemSusChem 14 (19) (2021 Oct 5) 4041–4070.

[133] Y. Jing, Y. Wang, S. Furukawa, J. Xia, C. Sun, M.J. Hülsey, H. Wang, Y. Guo, X. Liu, N. Yan, Towards the circular economy: Converting aromatic plastic waste back to arenes over a Ru/Nb2O5 catalyst, Angew. Chem. Int. Ed. 60 (2021) 5527–5535.

[134] Y. Kratish, J. Li, S. Liu, Y. Gao, T.J. Marks, Polyethylene terephthalate deconstruction catalyzed by a carbon-supported single-site molybdenum-dioxo complex, Angew. Chem. Int. Ed. 59 (2020) 19857–19861.

[135] L.D. Ellis, S.v. Orski, G.A. Kenlaw, A.G. Norman, K.L. Beers, Y. Román-Leshkov, G. T. Beckham, Tandem heterogeneous catalysis for polyethylene depolymerization via an olefin-intermediate process, ACS Sustain. Chem. Eng. 9 (2021) 623–628.

[136] A.C. Fernandes, Reductive depolymerization of plastic waste catalyzed by Zn (OAc)2 2H2O, ChemSusChem 100514 (2021).

[137] M. Roosen, K.M. MysN, P. Billen, A. Dumoulin, et al., Detailed analysis of the composition of selected plastic packaging waste products and its implications for mechanical and thermochemical recycling, Environ. Sci. Tech. 54 (2020) 13282–13293.

[138] V. Dufaud, J.M. Basset, Catalytic hydrogenolysis at low temperature and pressure of polyethylene and polypropylene to diesels or lower alkanes by a zirconium hydride supported on silica-alumina: a step toward polyolefin degradation by the microscopic reverse of Ziegler–Natta polymerization, Angew. Chem. Int. Ed. 37 (1998) 806–810.

[139] G. Celik, R.M. Kennedy, R.A. Hackler, M. Ferrandon, A. Tennakoon, et al., Upcycling single-use polyethylene into high-quality liquid products, ACS Cent. Sci. 5 (2019) 1795–1803.

[140] J.E. Rorrer, G.T. Beckham, Y. Roman-Leshkov, Conversion of polyolefin waste to liquid alkanes with Ru-based catalysts under mild conditions, JACS Au 1 (2020) 8–12.

[141] A. Tennakoon, X. Wu, A.L. Paterson, S. Patnaik, Y. Pei, et al., Catalytic upcycling of high-density polyethylene via a processive mechanism, Nat. Catal. 3 (2020) 893–901.

[142] C. Jia, S. Xie, I.NN. ZhangW, J. Sampath, et al., Deconstruction of high-density polyethylene into liquid hydrocarbon fuels and lubricants by hydrogenolysis over Ru catalyst, Chem Catal. 1 (2) (2021) 437–455.

[143] C. Jehanno, J. Demarteau, D. Mantione, M.C. Arno, F. Ruiperez, et al., Selective chemical upcycling of mixed plastics guided by a thermally stable organocatalyst, Angew. Chem. Int. Ed. 60 (2021) 6710–6717.

[144] H. Jung, G. Shin, H. Kwak, L.T. Hao, J. Jegal, H.J. Kim, D.X. Oh, Review of polymer technologies for improving the recycling and upcycling efficiency of plastic waste, Chemosphere 138089 (2023).

[145] J.C. Sadler, S. Wallace, Microbial synthesis of vanillin from waste poly (ethylene terephthalate), Green Chem. 23 (2021) 4665–4672.

[146] E. Santacruz-Juárez, R.E. Buendia-Corona, R.E. Ramírez, C. Sánchez, Fungal enzymes for the degradation of polyethylene: Molecular docking simulation and biodegradation pathway proposal, J. Hazard. Mater. 411 (2021) 125118.

[147] X. Chen, Y. Luo, X. Bai, Upcycling polyamide containing post-consumer Tetra Pak carton packaging to valuable chemicals and recyclable polymer, Waste Manag. 131 (2021) 423–432.

[148] K. Kremser, P. Gerl, A.B. Borrás, D.R. Espinosa, B.M. Martínez, G.M. Guebitz, A. Pellis, Bioleaching/enzyme-based recycling of aluminium and polyethylene from beverage cartons packaging waste, Resour. Conserv. Recycl. 185 (2022) 106444.

[149] G.L. Robertson, Recycling of aseptic beverage cartons: A review, Recycling 6 (1) (2021) 20.

[150] A. Pellis, G.M. Guebitz, D. Ribitsch, Bio-upcycling of multilayer materials and blends: closing the plastics loop, Curr. Opin. Biotechnol. 81 (2023) 102938.

[151] V. Beghetto, R. Sole, C. Buranello, M. Al-Abkal, M. Facchin, Recent advancements in plastic packaging recycling: a mini-review, Materials. 14 (2021) 4782.

[152] W. Zeb, M. Roosen, P. Knockaert, S. Janssens, D. Withoeck, M. Kusenberg, J. Hogie, P. Billen, S. Tavernier, K.M. Van Geem, S. De Meester, Purification and characterisation of post-consumer plastic pyrolysis oil fractionated by vacuum distillation, J. Clean. Prod. 21 (2023 Jun) 137881.

[153] A. Undri, L. Rosi, M. Frediani, P. Frediani, Fuel from microwave assisted pyrolysis of waste multilayer packaging beverage, Fuel 133 (2014) 7–16.

[154] K. Sivagami, G. Divyapriya, P. Ramya Selvaraj, N.S. Madhiyazhagan, I. Nambi, Catalytic pyrolysis of polyolefin and multilayer packaging based waste plastics: a pilot scale study, Process Saf. Environ. Prot. 149 (2021) 497–506.

[155] U. Bassey, K. Sarquah, M. Hartmann, A.-O. Tom, G. Beck, E. Antwi, S. Narra, M. Nelles, Thermal treatment options for single-use, multilayered and composite waste plastics in Africa, Energy 270 (2023) 126872.

[156] Y.I. Son, S.J. Yoon, Y.K. Kim, J.G. Lee, Gasification and power generation characteristics of woody biomass utilizing a downdraft gasifier, Biomass Bioenergy 35 (10) (2011 Oct 15) 4215–4220.

[157] F. Cao, L. Wang, R. Zheng, L. Guo, Y. Chen, X. Qian, Research and progress of chemical depolymerization of waste PET and high-value application of its depolymerization products, RSC Adv. 12 (49) (2022) 31564–31576.

[158] J. dos Passos, M.G. Souza, P. Biller, Screening of common synthetic polymers for depolymerization by subcritical hydrothermal liquefaction, Process Saf. Environ. Prot. 139 (2020) 371–379.

[159] E. Tito, J.S. dos Passos, S. Bensaid, R. Pirone, P. Biller, Multilayer plastic film chemical recycling via sequential hydrothermal liquefaction, Resour. Conserv. Recycl. 1 (197) (2023 Oct) 107067.

[160] R. Darzi, Y. Dubowski, J.L. Goldfarb, M. Karod, D. Sills, R. Posmanik, Hydrothermal processing of multilayer plastic film for cascaded valorization of nonrecyclable waste, ACS Sustain. Chem. Eng. (2023).

[161] T.W. Walker, N. Frelka, Z. Shen, A.K. Chew, J. Banick, S. Grey, et al., Recycling of multilayer plastic packaging materials by solvent-targeted recovery and precipitation, Sci. Adv. 6 (2020) eaba7599.

[162] V.S. Cecon, G.W. Curtzwiler, K.L. Vorst, A study on recycled polymers recovered from multilayer plastic packaging films by solvent-targeted recovery and precipitation (STRAP), Macromol. Mater. Eng. 307 (2022) 2200346.

[163] J. Demarteau, A.R. Epstein, P.R. Christensen, M. Abubekerov, H. Wang, S.J. Teat, et al., Circularity in mixed-plastic chemical recycling enabled by variable rates of polydiketoenamine hydrolysis, Sci. Adv. 8 (2022) eabp8823.

[164] S. Ügdüler, T. De Somer, K.M. Van Geem, M. Roosen, A. Kulawig, R. Leineweber, et al., Towards a better understanding of delamination of multilayer flexible packaging films by carboxylic acids, ChemSusChem 14 (2021) 4198–4213.

[165] Shiv Prasad, Krishna Kumar Yadav, Sandeep Kumar, Neha Gupta, Marina M.S. Cabral-Pinto, Shahabaldin Rezania, Neyara Radwan, Javed Alam, Chromium contamination and effect on environmental health and its remediation: A sustainable approaches. 2021 May 1; 285: 112174.

[166] P. Pandit, G.T. Nadathur, S. Maiti, B. Regubalan, Functionality and properties of bio-based materials, Green and sustainable advanced packaging materials, Bio-based materials for food packaging, 2018, pp. 81–103.

[167] M. Felix, V. Perez-Puyana, A. Romero, A. Guerrero, Development of protein-based bioplastics modified with different additives, J. Appl. Polym. Sci. 134 (2017) 45430.

[168] M. Asgher, S.A. Qamar, M. Bilal, H.M.N. Iqbal, Bio-based active food packaging materials: Sustainable alternative to conventional petrochemical-based packaging materials, Food Res. Int. 137 (2020) 109625.

[169] Y. Zhong, P. Godwin, Y. Jin, H. Xiao, Biodegradable polymers and green-based antimicrobial packaging materials: A mini-review, Adv. Ind. Eng. Polym. Res. 3 (2020) 27–35.

[170] A.C. Mendes, G.A. Pedersen, Perspectives on sustainable food packaging:–is bio-based plastics a solution? Trends Food Sci. Technol. 112 (2021) 839–846.

[171] S.M. Patil, N.R. Rane, P.O. Bankole, P. Krishnaiah, Y. Ahn, Y.-K. Park, K.K. Yadav, M.A. Amin, B.-H. Jeon, An assessment of micro- and nanoplastics in the biosphere: A review of detection, monitoring, and remediation technology, Chem. Eng. J. 15 (2) (2022 Feb) 132913.

[172] A. Samir, F.H. Ashour, A.A.A. Hakim, et al., Recent advances in biodegradable polymers for sustainable applications, Npj Mater Degrad 6 (2022) 68, https://doi.org/10.1038/s41529-022-00277-7.

[173] A. Bher, P.C. Mayekar, R.A. Auras, C.E. Schvezov, Biodegradation of biodegradable polymers in mesophilic aerobic environments, Int. J. Mol. Sci. 23 (20) (2022) 12165, https://doi.org/10.3390/ijms232012165.

[174] J.M. Nduko, S. Taguchi, Microbial production of biodegradable lactate-based polymers and oligomeric building blocks from renewable and waste resources, Front. Bioeng. Biotechnol. 8 (2021) 618077, https://doi.org/10.3389/fbioe.2020.618077.

[175] I. Vroman, L. Tighzert, Biodegradable polymers, Materials 2 (2) (2009) 307–344, https://doi.org/10.3390/ma2020307.

[176] I. Antonopoulos, G. Faraca, D. Tonini, Recycling of post-consumer plastic packaging waste in the EU: Recovery rates, material flows, and barriers, Waste Manag. 126 (2021) 694–705.

[177] Niraj R. Rane, Savita Tapase, Aakansha Kanojia, Anuprita Watharkar, El-Sayed Salama, Min Jang, Krishna Kumar Yadav, Mohammed A. Amin, Marina M.S. Cabral-Pinto, Jyoti P. Jadhav, Byong-Hun Jeon. Molecular insights into plant–microbe interactions for sustainable remediation of contaminated environment. Bioresource Technology. 2022 Jan; 334: 126246.

[178] M.H. Shafie, D. Samsudin, R. Yusof, C.Y. Gan, Characterization of bio-based plastic made from a mixture of Momordica charantia bioactive polysaccharide and choline chloride/glycerol based deep eutectic solvent, Int. J. Biol. Macromol. 15 (118) (2018 Oct) 1183–1192.

[179] F. Schmitz, M.B. de Albuquerque, M.D. Alberton, I.C. Riegel-Vidotti, L. M. Zimmermann, Zein films with ZnO and ZnO: Mg quantum dots as functional nanofillers: New nanocomposites for food package with UV-blocker and antimicrobial properties, Polym. Test. 1 (91) (2020 Nov) 106709.

[180] A. Chiloeches, R. Cuervo-Rodríguez, F. López-Fabal, M. Fernández-García, C. Echeverría, A. Muñoz-Bonilla, Antibacterial and compostable polymers derived from biobased itaconic acid as environmentally friendly additives for biopolymers, Polym. Test. 1 (109) (2022 May) 107541.

[181] P. Kongkaoroptham, T. Piroonpan, W. Pasanphan, Chitosan nanoparticles based on their derivatives as antioxidant and antibacterial additives for active bioplastic packaging, Carbohydr. Polym. 1 (257) (2021 Apr) 117610.

[182] V. Muralidharan, M.S. Arokianathan, M. Balaraman, S. Palanivel, Tannery trimming waste based biodegradable bioplastic: Facile synthesis and characterization of properties, Polym. Test. 1 (81) (2020 Jan) 106250.

[183] T. Jamnongkan, N. Kamlong, N. Thiangtrong, R. Mongkholrattanasit, Comparison the Physical and Antimicrobial Properties of Poly (Lactic Acid) Film and its Composites with ZnO Nanoparticles, Key Eng. Mater. 4 (772) (2018 Sep) 100–104.

[184] Shahabaldin Rezania, Junboum Park, Mohd Fadhil Md Din, Shazwin Mat Taib, Amirreza Talaiekhozani, Krishna Kumar Yadav, Hesam Kamyab. Microplastics pollution in different aquatic environments and biota: A review of recent studies. Marine Pollution Bulletin. 2018 Aug; 133: 191-208.

[185] M.F. Cosate de Andrade, P.M.S. Souza, O. Cavalett, A.R. Morales, Life cycle assessment of poly (lactic acid)(PLA): Comparison between chemical recycling, mechanical recycling and composting, J. Polym. Environ. 24 (2016) 372–384.

[186] J.D. Badia, A. Ribes-Greus, Mechanical recycling of polylactide, upgrading trends and combination of valorization techniques, Eur. Polym. J. 84 (2016) 22–39.

[187] C.L. Reichert, E. Bugnicourt, M.-B. Coltelli, P. Cinelli, A. Lazzeri, I. Canesi, et al., Bio-based packaging: Materials, modifications, industrial applications and sustainability, Polymers 12 (2020) 1558.

[188] S. Guzman-Puyol, J. Hierrezuelo, J.J. Benítez, G. Tedeschi, J.M. Porras-Vázquez, A. Heredia, A. Athanassiou, D. Romero, J.A. Heredia-Guerrero, Transparent, UV-blocking, and high barrier cellulose-based bioplastics with naringin as active food packaging materials, Int. J. Biol. Macromol. 1 (209) (2022 Jun) 1985–1994.

[189] European Bioplastics, Bioplastics market development update 2019 (2018–2019). https://www.european-bioplastics.org/new-market-data-2019-bioplastics-industry-shows-dynamic-growth/, 2019.

[190] G. Santagata, F. Valerio, A. Cimmino, G. Dal Poggetto, M. Masi, M. Di Biase, M. Malinconico, P. Lavermicocca, A. Evidente, Chemico-physical and antifungal properties of poly (butylene succinate)/cavoxin blend: Study of a novel bioactive polymeric based system, Eur. Polym. J. 1 (94) (2017 Sep) 230–247.

[191] P. Colombani, Life cycle assessment of different multilayer flexible food packagings with solventless adhesives, 2021.

[192] G. Koinig, E. Grath, C. Barretta, K. Friedrich, D. Vollprecht, G. Oreski, Lifecycle assessment for recycling processes of monolayer and multilayer films: a comparison, Polymers 14 (17) (2022) 3620.

[193] R. Vidal, P. Martínez, E. Mulet, R. González, B. López-Mesa, P. Fowler, J.M. Fang, Environmental assessment of biodegradable multilayer film derived from carbohydrate polymers, J. Polym. Environ. 15 (2007) 159–168.

[194] E. Pauer, M. Tacker, V. Gabriel, V. Krauter, Sustainability of flexible multilayer packaging: Environmental impacts and recyclability of packaging for bacon in block, Cleaner Environ. Syst. 1 (2020) 100001.

[195] V. Siracusa, C. Ingrao, A.L. Giudice, C. Mbohwa, M. Dalla Rosa, Environmental assessment of a multilayer polymer bag for food packaging and preservation: An LCA approach, Food Res. Int. 62 (2014) 151–161.

[196] M. Stramarkou, C. Boukouvalas, P. Eleni, D. Karalekas, M. Krokida, Comparative life cycle assessment of polyethylene terephthalate (PET) and multilayer Tetra Pak juice packaging systems, Chem. Eng. Trans. 87 (2021) 103–108.

[197] R. Banerjee, S.S. Ray, Sustainability and life cycle assessment of thermoplastic polymers for packaging: a review on fundamental principles and applications, Macromol. Mater. Eng. 307 (6) (2022) 2100794.