



# Mechanical recycling of polyamides: a review

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## ABSTRACT

This review addresses the importance and challenges of mechanical recycling of polyamides, highlighting its relevance within the global context of the circular economy. It begins by outlining the general characteristics, history, classification, molecular structure, and economic aspects of commercial polyamides. The focus then shifts to the polyamide recycling methods, including chemical and energy recovery, with a focus on mechanical processes, essential for effectively implementing the circular economy by reducing dependence on virgin resources and minimizing environmental impact. The final section summarizes relevant research on the mechanical recycling of polyamides across various industrial sectors. The examples mentioned in the studies here presented demonstrate that polyamides can be successfully recycled from reinforced composites, food packaging, and textiles, underscoring their potential to enhance sustainability while maintaining polymer quality through careful management of moisture content, extrusion cycles, and other parameters. Further research should concentrate on optimizing the separation of polyamides from other materials, minimizing degradation through controlled moisture levels and extrusion cycles, and exploring innovative recycling approaches across diverse applications. Overall, this article provides a comprehensive examination of mechanical recycling for polyamides, bringing studies with new and applicable technologies in this field to promote sustainability and address challenges associated with plastic waste.

## 1. Introduction

The significance of plastics in modern society is undeniable, with no predictions that their use will decrease over time (Geyer et al., 2017). Researchers estimate that more than 9 billion tons of virgin plastics were produced from the inception of industrial plastics manufacturing until 2019 (OECD, 2022). Fig. 1 shows the estimated global plastics production for 2022, which reached more than 400 million tons only that year. The data is categorized by material source, regional production, and polymer type. The polyolefins, including polyethylene (PE) and polypropylene (PP), dominate global thermoplastic consumption (Marangoni Júnior et al., 2023; Turriziani et al., 2023), being packaging the largest end-use market in Europe.

The exponential rise in plastic production has inevitably led to a significant increase in waste generation that requires effective management. According to the OECD Global Plastic Outlook (OECD, 2022), global plastic waste reached 353 million tons in 2019, more than doubling since 2000. Alarming, only 9 % of this waste was recycled, while nearly half ended up in landfills. If current trends continue, an

estimated 12 billion tons of plastic waste could be in landfills or the environment by 2050, highlighting the urgent need to address this issue (Priya et al., 2023).

The over-exploitation of non-renewable resources, combined with the excessive generation and landfill disposal of plastic waste, has escalated into a significant global environmental crisis. This situation underscores that the traditional linear economy model of “extraction-manufacturing-disposal” is no longer sustainable, necessitating a shift toward a circular economy. A circular economy emphasizes the reduction and recirculation of natural resources, fostering a more sustainable economic system (Corona et al., 2019; Plastics Europe, 2020). Through material recycling, we can recover raw materials from waste and reduce greenhouse gas emissions. Additionally, the circular economy can be advanced by utilizing renewable energy sources and adopting strategies that prioritize product redesign, waste reduction, efficient resource cycling, and extended product lifespans (Ellen MacArthur Foundation, 2016). Fig. 2 illustrates a diagram with the main routes that plastics can follow, considering a more circular economy, from manufacturing to disposal.

Fig. 2 highlights that mechanical recycling is one of the most

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**List of abbreviations:**

ASTM = American Standard Test Method  
 CaCO<sub>3</sub> = Calcium carbonate  
 CAS number = Chemical Abstracts Service registry number  
 CF = Carbon fibers  
 DSC = Differential Scanning Calorimetry  
 EVA = Ethylene–vinyl acetate copolymer  
 EVOH = Ethylene–vinyl alcohol copolymer  
 FTIR = Fourier-transform infrared spectroscopy  
 GF = Glass fibers  
 HDPE = High-Density Polyethylene  
 LDPE = Low-Density Polyethylene  
 LLDPE = Linear Low-Density Polyethylene  
 MA = Maleic anhydride

Mt = Million tons  
 NMR = Nuclear magnetic resonance  
 NWF = Nonwoven Fabric  
 PA = Polyamide  
 PE = Polyethylene  
 PE-g-MAH = polyethylene-graft-maleic anhydride  
 PET = Polyethylene terephthalate  
 PP = Polypropylene  
 PS = Polystyrene  
 PVC = Polyvinyl chloride  
 PVDC = Polyvinylidene chloride  
 SBR = Styrene butadiene rubber  
 SEM = Scanning Electron Microscopy  
 TGV = Thermogravimetric analysis

effective ways to manage plastic waste, yet it faces significant challenges. These include the complexities and costs of collecting and sorting plastics, contamination from mixed waste, the low cost of virgin materials, and incompatibility of certain polymers (Maris et al., 2018). For instance, PE and PA are generally incompatible due to their differing polarity and molecular structures, which result in poor adhesion and phase separation during processing. Other common examples include PET and polyolefins (such as PE or PP), which also require compatibilizers or separation for effective recycling. In response, research is increasingly focused on developing new technologies and recycled materials, yielding promising results that offer environmentally and economically beneficial solutions for producing plastic products from recycled materials (Czarnecka-Komorowska et al., 2021).

Polyamides (PA), commonly known as nylons, are a versatile family of semicrystalline thermoplastics typically derived from petroleum-based monomers such as hexamethylenediamine, adipic acid, and caprolactam. They are widely used across various industries, including fiber production, the manufacturing of mechanical and electrical components, and flexible packaging due to their mechanical strength, transparency, thermal and barrier properties. PAs are classified under “other” in the polymer’s classification (Fig. 1), and represent approximately 1.5 % of total global plastic use (Heinrich Böll Foundation, 2019). While this percentage may seem small compared to more dominant plastics, it represents a significant volume in terms of total production, underscoring their ongoing relevance. The anticipated expansion of the global PA market to 10.4 million tons annually by 2027 presents a significant sustainability challenge. This growth raises concerns due to the non-biodegradable nature of polyamide waste, which are generally resistant to biodegradation due to their strong covalent amide bonds and high crystallinity, which make them difficult to break down into harmless components under typical environmental conditions (e.g., in soil or water) within a reasonable time.

Additionally, PAs are often combined with other materials in multilayer structures to enhance overall performance by leveraging their unique properties, such as thermal, mechanical and oxygen barrier properties. Furthermore, due to the PAs poor water vapor barrier properties, they are frequently combined with materials that offer better moisture resistance. These multilayer combinations allow packaging materials to be tailored for specific applications, balancing protection, durability, and processing requirements. However, those combinations also may lead to poor compatibility during recycling. Consequently, developing effective and sustainable recycling technologies has become imperative (Lozano-Gonzalez et al., 2000; Minor et al., 2023).

Several recycling options for PAs are currently available, including mechanical, chemical, and energy recovery recycling, which are the three predominant approaches. Two review articles on polyamide recycling were recently published (Hirschberg & Rodrigue, 2023; Tonsi

et al., 2023), providing an overview of the leading recycling methods and their respective challenges. However, neither focused specifically on mechanical recycling, which is the focus of our work, due to its distinct environmental advantages over the other methods.

Mechanical recycling is usually considered the best environmental choice, being widely studied, as it requires less energy input and avoids the chemical transformation or combustion steps associated with higher greenhouse gas (GHG) emissions. By preserving the polymer structure through physical reprocessing steps - such as shredding, melting, and extrusion - it enables the reuse of materials in new products, thereby reducing the demand for virgin polymer production and minimizing waste. This approach significantly lowers emissions of GHGs such as carbon dioxide (CO<sub>2</sub>), which are typically released during fossil-based monomer production and incineration processes (Maris et al., 2018; Minor et al., 2023).

This review synthesizes important findings from existing literature to thoroughly examine the mechanical recycling of polyamides. Through this analysis, we have aimed to highlight the opportunities and challenges inherent in this process and offer insights into the current state of this field.

## 2. Polyamides – main characteristics

### 2.1. History

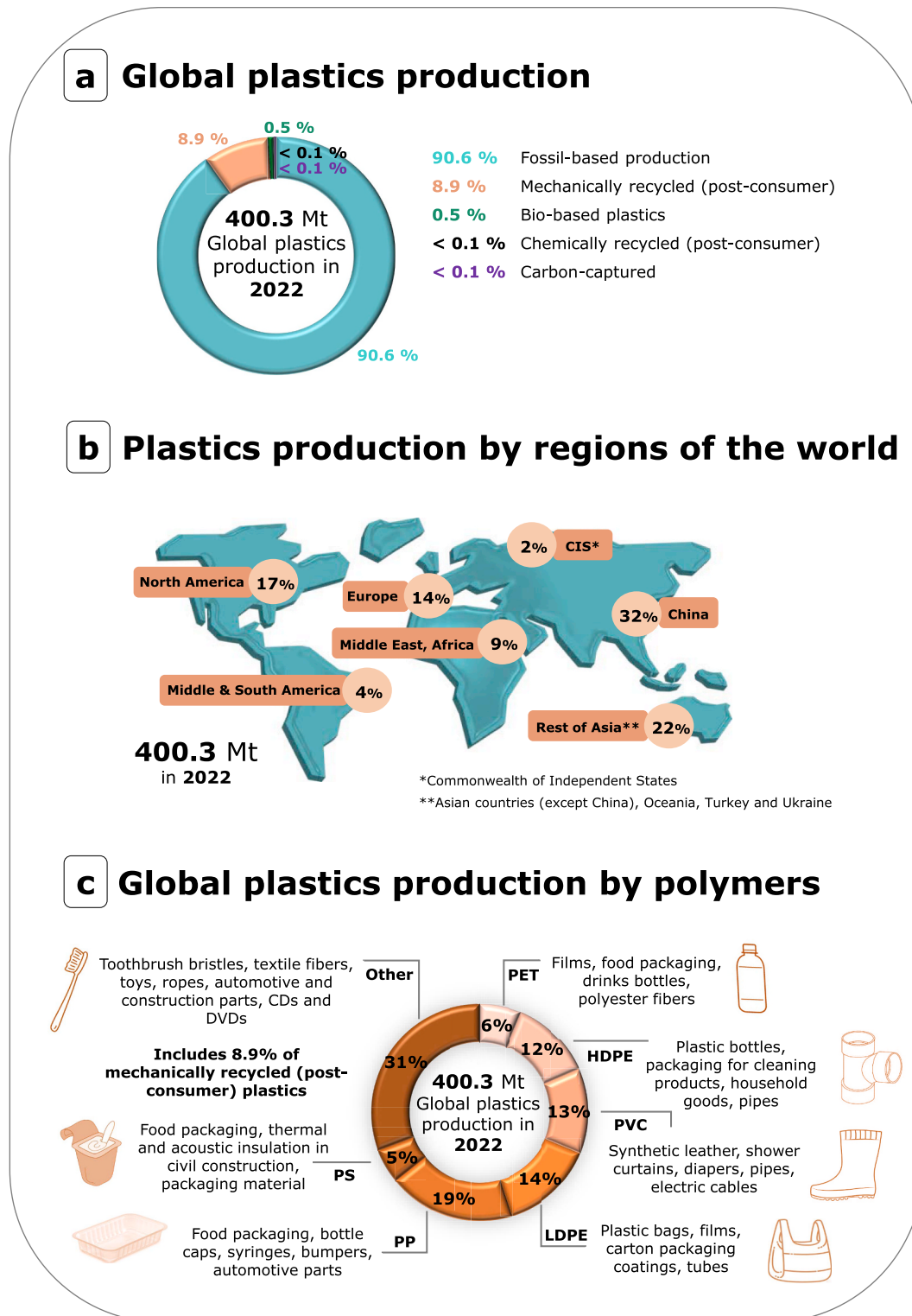
PA 66, or poly(hexamethylene adipamide), was the first commercial engineering thermoplastic. It was invented by the American chemist Wallace Hume Carothers and collaborators between 1928 and 1937 at DuPont, an American chemical company, after much research into the condensation polymerization process, being named “nylon 66” (I. B. Page, 2000).

Carothers played a pivotal role as a group leader in creating Nylon 66 (PA66), partly motivated by the Japanese silk monopoly during the late 1930s, encouraging the search for alternative materials (Parodi, 2017). Its commercialization began in 1938 with the production of toothbrush monofilaments, followed by the production of fibers in 1939. Nylon was the first synthetic polymer introduced in the market, being instantly successful and of particular importance during the manufacture of clothing and objects (parachutes, tents) in the Second World War. Nylons became commercially available for the packaging market in the 1950s (Deopura & Padaki, 2015; Sarantópoulos & Teixeira, 2017a, 2017b). Nowadays, PAs are extensively utilized in flexible multilayer packaging, frequently combined with polyolefins. Critical attributes of PA include strong mechanical performance such as tensile strength and elongation at break, thermal resistance, and effective oxygen barrier properties (Marangoni Júnior et al., 2020b; Oliveira, et al., 2020; Tyufitin & Kerry, 2020).

Polyamide 6 (polycaprolactam) was first produced by J. Von Brown at Gottingen University between 1905 and 1910. Several years later, P. Schlack secured numerous patents concerning the catalytic polymerization of caprolactam into Polyamide 6, earning recognition as the inventor of commercial PA6 (I. B. Page, 2000).

The pioneering nature of their inventions primarily explains the

dominance of PA6 and PA66 in the market. Nonetheless, numerous other polyamides have been developed and commercialized since their development using a combination of different starting materials (Gong et al., 2021).



**Fig. 1.** Estimation of global plastics production at the year of 2022, indicating: a) the material source, b) the production by regions of the world, and c) the production by polymer source, with their main application. HDPE = High-Density Polyethylene; LDPE = Low-Density Polyethylene; PET = Polyethylene terephthalate; PP = Polypropylene; PS = Polystyrene; PVC = Polyvinyl chloride. Adapted from (Heinrich Böll Foundation, 2019; Plastics Europe, 2023).

## 2.2. General characteristics, classification and commercial uses of polyamides

As previously mentioned, the origin of commercial polyamide development can be traced back to W. H. Carothers' pioneering research on condensation polymerization, which led to the production of PA66. In this process, monomers undergo a condensation reaction that results in the elimination of a small molecule. Although polyamides do occur naturally, as in the self-condensation of amino acids, they are primarily produced synthetically - either through the condensation of a diamine with a dicarboxylic acid (Scheme 1), as in the case of PA66, or through the ring-opening polymerization of a lactam, as in the case of PA6 (Herzog et al., 2013; Saunders, 1988a, 1988b).

In Scheme 1, 'R' denotes hydrocarbon chains bridging the functional groups, defining the polymer's characteristics; 'n' represents the degree of polymerization or the count of recurring groups within the polymer chain (I. B. Page, 2000). The distinguishing features and properties among different PAs stem from their polymeric structure, determined by the raw materials employed in their production. PAs formed from two monomers are designated with a nomenclature of PA X,Y: 'X' indicates the number of carbons in the diamine monomers, while 'Y' represents the number of carbons in the diacid monomer, for example, PA6,6 (or PA66, as adopted in this work). On the other hand, PAs produced via the ring opening of a dual functional monomer, such as caprolactam, are denoted as PA Z: 'Z' indicates the number of carbons in the monomer, such as PA6 (Deopura & Padaki, 2015; Ogunsona et al., 2019; Saunders, 1988a, 1988b). Table 1 summarizes the characteristics of the main aliphatic polyamides, while Scheme 2 illustrates their molecular structures.

The distance between the repeats of the polar -CONH- group affects the properties of polyamides. As the length of the aliphatic segment (the number of methylene groups between the amino groups in the chain) increases, i.e., as the number of PA increases, there is a reduction in density, melting point, tensile strength, and water absorption, as well as an increase in elongation, impact resistance, and permeability (Robertson, 2013; Sarantópoulos & Teixeira, 2017a, 2017b).

In addition to the property data for polyamides presented in Table 1, critical for applications in sectors like automotive and civil construction, other factors such as degree of crystallinity and permeability to oxygen and water vapor are vital for specific uses in packaging and multilayer films. These properties offer valuable insights into the potential applications of polyamides, particularly in food packaging and other products that require efficient barrier performance. Crystallinity, in particular, informs several key characteristics, including mechanical strength, thermal stability, chemical resistance, transparency, density, and overall durability. Understanding the degree of crystallinity is essential for

predicting polymer performance and customizing its properties for various applications. For context, the degree of crystallinity for PA66 is approximately 70 %, while PA6 has a degree of about 67 % (Deopura, 2008).

PAs offer several commercial advantages, primarily due to their favorable mechanical and chemical properties. Mechanically, they exhibit high tensile strength, excellent wear and impact resistance, and outstanding abrasion resistance. Chemically, PAs demonstrate strong stability against solvents, acids, and bases, as well as exceptional resilience to fuels, greases, and oils. Additionally, they provide excellent oxygen barrier performance, making them suitable for demanding applications. As shown in Table 1, PAs are used across a wide range of sectors, with the automotive and electrical/electronic industries being the most prominent (Ogunsona et al., 2019). PA6 and PA66 account for approximately 95 % of total PA usage in the industry, while their analogs (PA69, 610, 612, 11, and 12) are typically considered high specialty products with higher price points (I. B. Page, 2000; Plastics Europe, 2020).

In the automotive sector, which increasingly demands lighter materials and greater efficiency, PAs are utilized in components such as radiators, cooling systems, engine covers, fuel lines, fuel pumps, lighting, and electrical systems (Kondo et al., 2022). In the electrical and electronics industry, PAs are valued for their impressive thermal resistance and electrical insulation properties, including low flammability and high surface resistivity (I. B. Page, 2000). Textiles and fibers were among the first applications for PAs; PA fibers are widely used in fashion and apparel due to their advantages over other fibers, including affordability, durability, strength, and flexibility (Abdelwahab et al., 2022; Deopura & Padaki, 2015).

Moreover, PAs are crucial in modern packaging, particularly in the production of extruded films, which can be either mono- or biaxially oriented. PA6 and PA66 are the most commonly used for films because of their favorable properties (Krishna et al., 2021). Their role in flexible multilayer packaging highlights their excellent mechanical performance, thermal resistance, and barrier properties against gases and aromas (Marangoni Júnior et al., 2020b; Tyufin and Kerry, 2020). However, they have limitations, such as poor water vapor barrier properties and diminished mechanical and barrier performance when exposed to moisture (Sarantópoulos & Teixeira, 2017a, 2017b). To address these limitations in packaging applications, PA films are often incorporated into multilayer coextruded structures or laminated with polyolefins, EVA, or ionomers to improve their water vapor resistance, leading to tailored packaging solutions (Marangoni Júnior et al., 2020a). The final properties of multilayer packaging are significantly influenced by the combination of materials used, allowing for enhanced overall performance (García Ibarra et al., 2019).

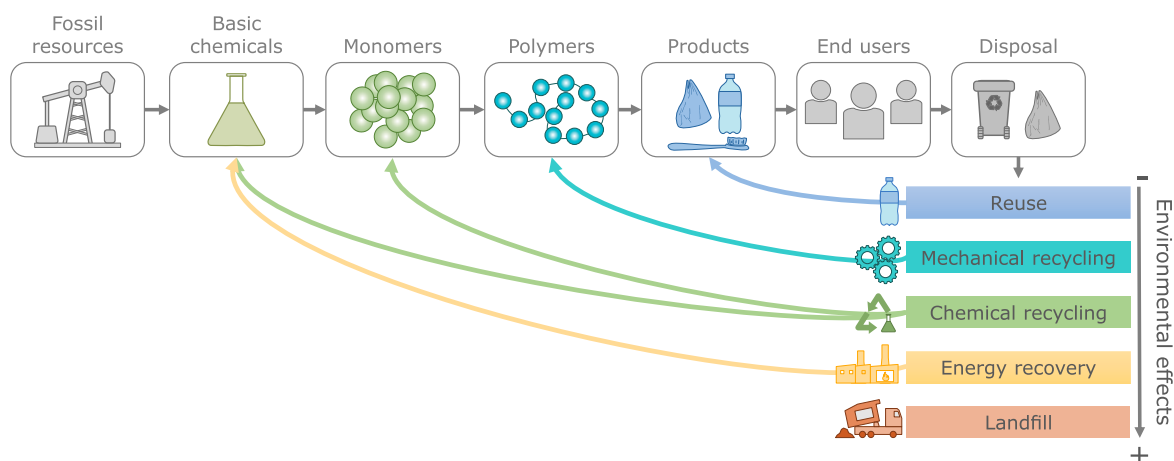
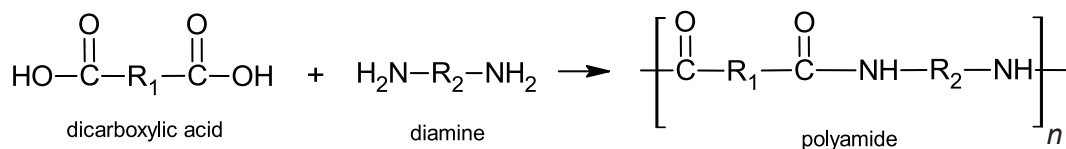


Fig. 2. Main steps from generation to disposal of plastics, including recycling routes. Adapted from (Dijkstra et al., 2020; Maris et al., 2018; Minor et al., 2023).



**Scheme 1.** Formation and nomenclature of a typical polyamide molecule, adapted from (Herzog et al., 2013).

The versatility of flexible multilayer packaging with PAs makes them particularly well-suited for vacuum packaging of proteins and cheese, where maintaining freshness and extending shelf life are essential. Beyond packaging films, PA films are also widely used in food-related applications such as modified atmosphere packaging (MAP), where specific gas mixtures help preserve perishable items. Additionally, they are used in thermoformed tray lids and other high-barrier food packaging solutions (Tyuftin & Kerry, 2020). Furthermore, PAs facilitate in-package food processing, offering advantages in conventional thermal treatments such as pasteurization and sterilization. This approach helps mitigate post-processing contamination risks and reduces the need for costly aseptic packaging lines (Marangoni Júnior et al., 2023; Marangoni Júnior et al., 2020b).

In summary, PAs are fundamental in many industries, particularly packaging, providing essential properties that ensure product integrity, safety, and extended shelf life across a wide range of food and non-food applications.

### 3. Recycling of polyamides

Polyamides can be recycled by different approaches, being the main ones mechanical and chemical. This work primarily explores mechanical recycling studies, elucidating their processes and main achievements. Nonetheless, a brief overview of the other recycling techniques is also provided to clarify their main characteristics and differences concerning the mechanical process. It is important to mention that, in our text, the terminology used to define each type of recycling is in accordance with the classification standardized by ISO for mechanical and chemical recycling (Hopewell et al., 2009), the American Society for Testing and Materials (ASTM) definition for each case is also described, as shown in Table 2.

#### 3.1. Specifications, properties and quality control

Before exploring recycling methods, it is crucial to ensure that the resulting products meet the quality criteria set by regulatory agencies and industrial producers.

Polymer properties are key indicators in both lab analyses and industrial applications. Understanding the main characteristics of newly obtained polymers, whether through conventional means or recycling, helps researchers establish structure-property relationships. In industrial settings, properties like melt viscosity and heat capacity are important for setting polymerization and processing conditions. It is also vital to comprehend polymer degradation during recycling to determine appropriate recycling processes.

Therefore, having access to key material properties - such as viscosity, moisture content, and ash content for reinforced grades - is essential for selecting appropriate polymers for specific applications (Ellis & Smith, 2008; Yap et al., 2024). For polyamides, standards such as ASTM D4066 and ISO 1874-1/2 provide classification and specification guidelines, outlining the relevant tests and methodologies to evaluate these parameters.

Another important consideration is the specific legislation of each region where the packaging will be used, particularly if it's intended for direct food contact. In the EU, Regulation (EC) No 1935/2004 establishes general safety principles for Food Contact Materials (FCMs), while

Commission Regulation (EU) No October 2011 focuses on plastic materials, and Regulation (EU) 2022/1616 addresses recycled materials in food contact (European Union, 2011, 2022). In the U.S., relevant rules are outlined in Title 21 of the Code of Federal Regulations (CFR), with Parts 177 and 178 covering indirect food additives and Parts 182, 184, and 186 listing GRAS substances, among others (CFR, 2024). In South America, MERCOSUR countries follow regional regulations developed by the Common Market Group, particularly through Working Subgroup SGT 3, which addresses food contact packaging (MERCOSUR, 2024). Each member country also has national regulations; for instance, Brazil's ANVISA resolution No. 91/2001 aligns with MERCOSUR resolution GMC 03/92.

All regulations are crucial for ensuring that plastic materials are safe and meet rigorous quality standards, especially the materials used in food packaging. They also support using recycled materials in packaging while maintaining food safety, thus contributing to sustainable practices in the packaging industry.

#### 3.2. Non-mechanical recycling of polyamides

The non-mechanical recycling of polyamides involves chemical (tertiary) and energy recovery (quaternary) methods (Table 2).

Chemical recycling refers to processes that chemically transform polymer chains into smaller molecules (monomers, oligomers, or other lower molecular weight compounds) suitable for feedstock in producing new polymers, fuels, or other chemicals. The methods usually involve depolymerization processes, such as glycolysis, methanolysis, hydrolysis, and aminolysis. Thermal approaches, such as pyrolysis and gasification, also play a role by breaking bonds within the polymer backbone (Maris et al., 2018). More recently, hydrothermal technology has emerged as an efficient depolymerization method, particularly for polyamides (PAs), leveraging subcritical or supercritical water conditions to break down polymers into valuable monomers (Laredo et al., 2023). In this way, chemical recycling enables both the "recycling" and "upcycling" of plastic materials that are unsuitable for mechanical recycling (Minor et al., 2023).

Research into the chemical recycling of polyamides dates back to the early 1960s. According to a review by Coates and Getzler (Coates & Getzler, 2020), polyamide 6 (PA6) is an excellent candidate for chemical depolymerization due to its lack of thermodynamic or kinetic limitations. Various chemical depolymerization pathways have been explored for polyamides (Chanda, 2021; Datta & Kopczyńska, 2016; Minor et al., 2023). However, only a small fraction of annual PA6 production undergoes chemical recycling (Coates & Getzler, 2020; Maisels et al., 2021). This is attributed to the limited economic viability of depolymerization processes (Alberti et al., 2019; Kamimura et al., 2014). Therefore, there is a need for a techno-economic analysis of PA6 chemical recycling, which is currently absent in the literature.

Energy recovery involves converting plastic waste into heat and/or electricity, commonly through incineration. Globally, this method has become a significant strategy for managing post-consumer plastic waste, with approximately 19 % being incinerated by 2019 (OECD, 2022). It is especially viable when mechanical recycling is not feasible due to contamination, poor separation, or degradation of polymer properties (Maris et al., 2018). Another thermochemical method is gasification, which transforms plastic waste into syngas - a mixture of hydrogen and

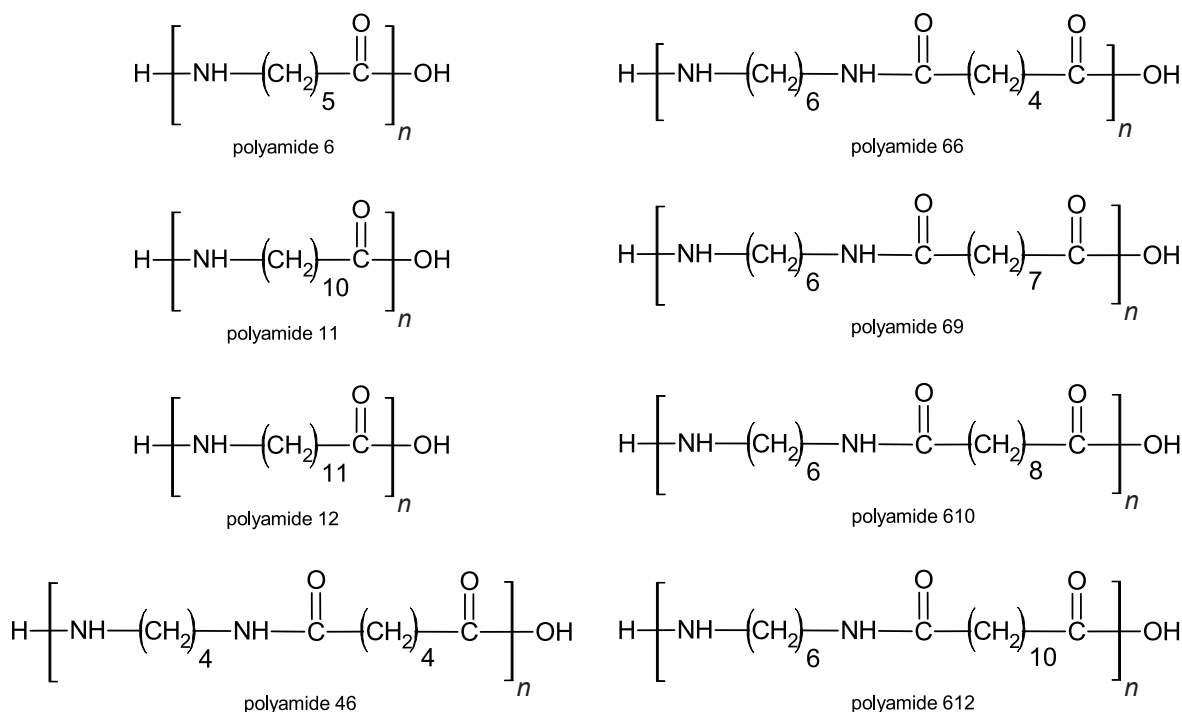
**Table 1**

Main characteristics and properties of some commercially available polyamides.

Name	CAS number	Monomers <sup>b</sup>	Melting point (°C) ASTM D2117 <sup>b</sup>	Water absorption (wt% 24h) <sup>b</sup>	Specific gravity (g/cm <sup>3</sup> ) ASTM D792 <sup>a</sup>	Tensile yield strength (MPa) ASTM D638 <sup>b</sup>	Elongation at break (%) ASTM D638 <sup>b</sup>	Properties <sup>c</sup>	Main applications <sup>c</sup>
Nylon-6,6; PA66	32131-17-2	Hexane-1,6-diamine; Adipic acid	255	1.2	1.14	83	60–90	Relatively high melting point and glass transition temperatures; high mechanical strength and rigidity (toughness); chemical resistance	Food packing films; electro-insulating; machine parts; automotive industry (engine parts, fuel filters, airbags, etc.)
Nylon-6; PA6	25038-54-4	ε-Caprolactam	215	1.6	1.13	81	50–150	High toughness; low coefficient of friction; resistant to chemicals and abrasion; bear high loads at high temperature	Food packing films; different types of containers; electrical switches; bobbins; connectors; automotive parts; etc.
Nylon-11; PA11	25035-04-5	11-Aminoundecanoic acid	194	0.3	1.03	55	200	Low specific gravity; high impact resistance; low moisture absorption; resistant to hydrolytic reagents and UV; dimensionally stable; more expensive than other polyamides	Used in several industrial and automotive sectors and for flexible pipes for offshore oil transportation (add resistance to marine corrosion)
Nylon-12; PA12	24937-16-4	Dodecanolactam; 12-aminododecanoic acid	179	0.25	1.02	55	200	Low moisture absorption; low density; chemical resistance; very resistant to stress cracking (flexible); excellent impact resistance when in dry state and low temperatures	Several applications in the automotive and electrical industry
Nylon-6,9; PA69	28757-63-3	Hexamethylenediamine; Azaleic acid	205	0.5	1.08	55	125	Low melting point allowing a wide processing range; low moisture absorption and good dimensional stability <sup>a</sup>	Electrical connectors; banners; luggage bags; furniture <sup>a</sup>
Nylon-6,12; PA612	24936-74-1	Hexamethylenediamine; Dodecanedioic acid	212	0.25	1.06	61	150	Good thermal, mechanical and electrical properties in most environments; dimensional stability, chemical resistance	Its broad spectrum of applications encompasses both structural and electrical components; toothbrush monofilaments
Nylon-4,6; PA46	50327-22-5	1,4-Diaminobutane; Adipic acid	298	2.0	1.12	95	>50	High moisture regain; resistant to high temperatures, presenting high tensile strength, heat deflection, and tenacity	Frequently combined with glass fiber or polytetrafluoroethylene, being applied in various automotive components
Nylon-6,10; PA610	9011-52-3	Hexamethylenediamine; Sebacic acid	215 <sup>d</sup>	2.4 <sup>d</sup>	1.07	55 <sup>a</sup>	100–150 <sup>d</sup>	Good chemical and thermal resistance <sup>a</sup>	Jacketing for cables and tubing (flame-retardant); weather resistant grades for fittings; monofilaments for brushes <sup>a</sup>

## References.

<sup>a</sup> (I. B. Page, 2000).<sup>b</sup> (Palmer, 2002).<sup>c</sup> (Francisco et al., 2019).<sup>d</sup> (Saunders, 1988a, 1988b). ASTM = American Standard Test Method; CAS number = Chemical Abstracts Service registry number.



**Scheme 2.** Molecular structure of some commercially available polyamides. Adapted from (Deopura, 2008; Lee & Kim, 2016; Saunders, 1988a, 1988b).

**Table 2**

Terminology applied for each category of plastic recycling.

Standard ISO 15270	Standard ASTM D7209–06	Definitions
Mechanical recycling	Primary recycling	Reintroduction of industrial residues in the process; extrusion of the material in the same plant/company it is processed
	Secondary recycling	Mechanical recycling of post-consumer waste
Chemical recycling	Tertiary recycling	Chemical conversion of plastic waste into feedstock
Energy recovery	Quaternary recycling	Valorization: incineration of plastic waste and production of energy

carbon monoxide - that can be used for energy production or as feedstock in chemical manufacturing (Brems et al., 2015). Although energy recovery is not classified as recycling under EU regulations, the high calorific value of plastic waste makes these methods attractive for diverting non-recyclable plastics from landfills while recovering energy.

Very often, polyamides are combined with other polymers (such as polyesters, polypropylene, or polyurethanes) or inorganic/organic fillers (such as TiO<sub>2</sub>, glass fibers, carbon black, dyes, etc.) to give the desired properties or aspects to the final products. In this context, the mechanical recycling of these materials – an attractive technique due to its low energy demand and costs – may be a challenging option. Therefore, a possible – but not ideal – solution to deal with polyamide wastes could be the energy recovery approach, such as incineration and gasification (Maris et al., 2018; Tonsi et al., 2023). There are ways to overcome these challenges inherent to the mechanical recycling of polyamides, as will be further discussed, including examples of case studies.

### 3.3. Mechanical recycling of polyamides

Mechanical recycling represents the predominant approach for handling plastic waste, involving processes that recover pre- or post-consumer plastics through mechanical means. This method allows for

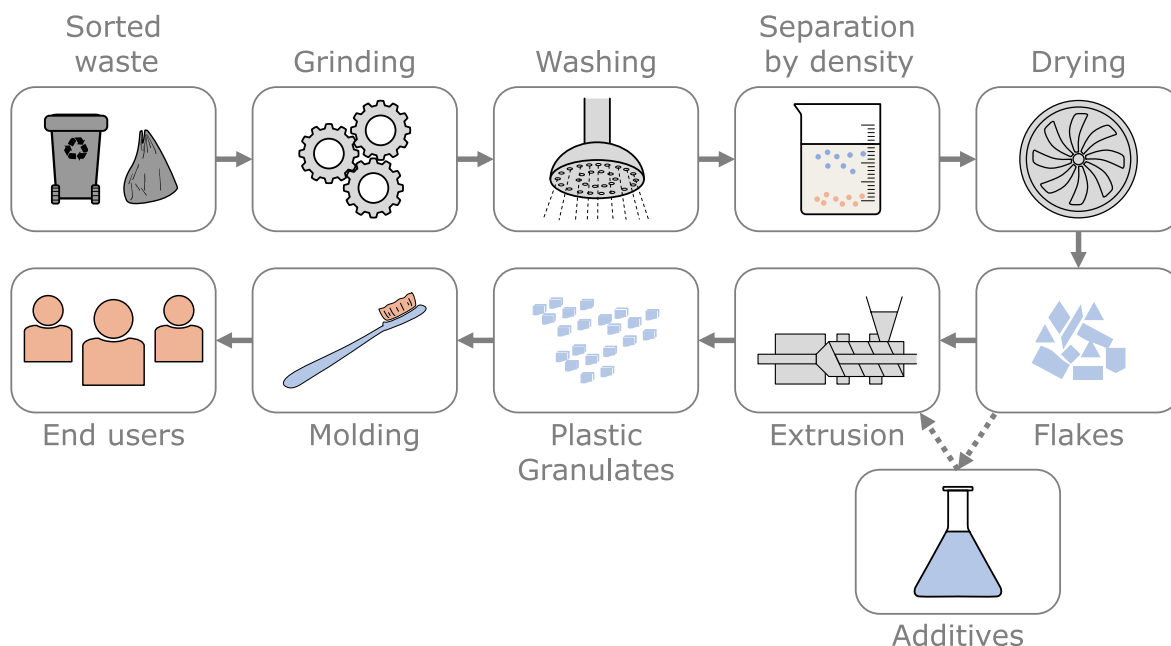
the transformation of recycled materials into new plastic products, potentially replacing virgin polymers entirely or partially (Maris et al., 2018). However, it is important to mention that repeated processing and exposure to heat, shear, and contaminants can degrade the polymer's molecular structure, often leading to inferior mechanical properties and limiting the material's suitability for high-performance applications - a phenomenon known as downcycling.

The mechanical recycling process typically begins with collecting, sorting, and cleaning the plastic waste, followed by a size reduction using multi-shaft shredders and cutters, which chop, shatter, and grind the plastic into small pieces. After reducing the size of the material, there is a washing step and a separation of the pieces obtained by density. The material is then sieved, dried, and goes to the extrusion step, being processed through melt processing, the use of additives being an optional step at this stage (Recyclclass, 2023). The sequence of the mechanical recycling steps may vary depending on the source and composition of the waste, as illustrated in Fig. 3.

Although costly waste separation and cleaning requirements are hindered, mechanical recycling methods are recognized for their speed, scalability, and lack of direct CO<sub>2</sub> emissions or waste gases, offering a straightforward route for recycling polyamides (Hirschberg & Rodrigue, 2023). Special attention, however, should be given to the repeated melt processing and the presence of water, which can accelerate the degradation of PA properties, as will be discussed later (Chanda, 2021). Despite these challenges, mechanical recycling remains a viable method for valorizing PAs waste, offering an economical, large-scale, and solvent-free approach, as recycled products' quality depends on initial material selection (Chanda, 2021; Mistretta et al., 2023).

#### 3.3.1. Challenges related to the mechanical recycling process

The processes related to the mechanical recycling (Fig. 3) of mono-layer and mixed plastics can deteriorate the material's properties under certain conditions, such as heat, oxidation, light exposure, and mechanical shear. The degradation induced by reprocessing (thermal-mechanical) is one of the most recurring ones in the mechanical recycling process due to the combined effects of heat and mechanical shear. The other form of degradation arises from long-term exposure to



**Fig. 3.** General overview of the steps involved in the mechanical recycling process. Adapted from (Colucci et al., 2015; Hirschberg & Rodrigue, 2023; RecycClass, 2023).

environmental factors, such as a combination of heat, oxygen, light, radiation, moisture, and mechanical stress, occurring throughout the product's lifetime (Maris et al., 2018; Ragaert et al., 2017). An additional hurdle in recycling mixed plastic waste lies in the variations in melting points and processing temperatures among mixed polymers. When reprocessing these blends, recyclers frequently operate at the processing temperature of the polymer with the highest melting point. This often results in overheating and degrading some of the lower melting components, consequently diminishing the final product's properties (Ragaert et al., 2017).

One approach to overcome those challenges involves introducing additional components during the melting process, such as virgin polymers, fillers, fibers, compatibilizers, or various additives like peroxides, coupling agents, reactive polymers, stabilizers, and antioxidants. These additives improve the material's properties and provide characteristics that facilitate their use as new materials within the plastics industry (Maris et al., 2018). Specifically in the case of PAs, the main problems faced during mechanical recycling are repetitive melting, the presence of water, and mixing with other polymers.

The repetitive melting process can cause severe degradation of the PA properties, although molecular weight (Mw) may increase or decrease depending on processing conditions - for example, Mw can increase due to condensation or trans-reactions. Mixing the recycled material with virgin polymer or adding a chain-extender can improve the final product quality (Chanda, 2021; Lozano-Gonzalez et al., 2000).

Moreover, PA degradation accelerates in the presence of moisture, promoting depolymerization and intensifying thermomechanical degradation. This synergy underlines the importance of thorough drying before melt processing, which increases the cost of recycling. Interestingly, this same moisture-induced depolymerization mechanism forms the basis of hydrothermal depolymerization, an emerging chemical recycling approach for PAs, previously mentioned in this review (Laredo et al., 2023). As an alternative to drying, antioxidants or stabilizers can also be used to reduce the impact of moisture during melt processing (La Mantia et al., 2002).

When PA is combined with other materials to achieve diverse mechanical properties, such as polyurethane, polyester, and glass fibers, the blends can pose difficulties for subsequent thermomechanical recycling. Some examples are illustrated in Table 3, item 3.3.2 below. Since

PA is usually the primary component and has a relatively high melting point (typically around 220–270 °C, depending on the type), re-extrusion must occur at elevated temperatures. This poses a risk of thermal degradation for co-blended polymers with lower thermal or chemical stability, such as polyurethane or certain polyesters. This degradation can lead to the formation of impurities that compromise the quality of the recycled product, limiting potential applications (Tonsi et al., 2023).

In contrast, when PA is not the primary material, as in multilayer packaging structures where it is combined with PE, the packaging can often be recycled following the same protocol as the main material. For example, in a PE + PA multilayer film consisting of approximately 75 % PE, less than 15 % PA, and up to 10 % of the PE is in the form of PE-g-MAH (maleic anhydride-grafted polyethylene) - as a compatibilizer - the structure can still be recycled in conventional PE recycling streams (RecycClass, 2021; RecycClass, 2022). In such cases, the use of compatibilizers plays a crucial role in enhancing compatibility between layers and improving recyclability.

A compatibilizer is an additional third component that exhibits miscibility with both phases (Turriziani et al., 2023, 2024). Its primary function is to optimize interfacial tension, stabilize morphology against high stresses, and enhance adhesion between phases in the solid state. However, finding “universal” compatibilizers that can maintain mechanical properties regardless of the nature and quantity of contaminants remains challenging (Czarnecka-Komorowska et al., 2021).

Another critical aspect that must be considered is that the environmental footprint of packaging can be overshadowed by the environmental footprint of the product it protects, highlighting the importance of optimizing product protection over enhancing recyclability alone. Pauer et al. (Pauer et al., 2020) investigated the environmental impacts and recyclability of six representative multilayer plastic packaging solutions used for bacon in block, a product known for its complex packaging needs. Despite the valuable protective properties of multilayer plastics containing PA, they pose significant recycling challenges and are often considered an environmental concern. The research employs a cradle-to-grave Life Cycle Assessment (LCA) to evaluate packaging options such as thermoformed films, vacuum bags, and shrink films based on their carbon footprints and recyclability using the RecycClass tool. This free online tool allows a theoretical assessment of the recyclability

**Table 3**

Overview of the literature works about mechanical recycling of polyamides.

Material	Source	Recycling process	Additives	Main achievements	Reference
PA6 (100 %)	Commercial resin	Processing in an injection molding machine, temperature of injection = 210–235 °C	No additives were used	The study on multiple recycling cycles of virgin PA6 in an injection molding machine revealed that the material can undergo up to seven cycles without significant effects on its physical and mechanical properties or morphology, demonstrating its resilience to recycling processes.	<a href="#">Lozano-Gonzalez et al. (2000)</a>
PA6 (100 %)	Commercial resin	Temperature profile for injection in molding machine = 220, 225, 230 and 235 °C; mold temperature = 80 °C	No additives were used	Virgin PA6 was reprocessed 16 times. The main results were related to the variations in crystalline characteristics between the virgin and processed PA6, and related to the mechanical properties of PA6 that transitioned gradually from being soft and tough to becoming hard and brittle after each processing cycle.	<a href="#">Su et al. (2007)</a>
PA6 (100 %)	Commercial resin	Extrusion with thermal profile with fixed temperature = 240 °C	Antioxidant: tetrakis-(2,4-ditert-butylphenyl)-4,4'-biphenylen-diphosphonite (Sandostab P-EPQ, Clariant) (500 ppm)	Reprocessing of polyamide in dry conditions resulted in secondary material with good properties even after several processes. Wet conditions, however, resulted in drastic reduction of molecular weight by hydrolytic chain scission. The antioxidant improved the recycling in wet conditions, showing better results than even dry conditions.	<a href="#">La Mantia et al. (2002)</a>
PA66 (70 %) + short carbon fibers (30 %)	Commercially available granules obtained by compounding extrusion (PA66CF30)	Injection molding with a melt temperature of 280 °C	Short carbon fibers (CF)	The results of mechanical, thermal and morphological investigations revealed that the recycling process had no significant effect on the final properties and microstructure of the recycled composites, being instead more degraded during aging. The obtained material was suitable for semi-structural applications in the automotive industry.	<a href="#">Colucci et al. (2015)</a>
PA66 (64.3 %) + short glass fibers (35.7 %)	Radiator parts coming from an end-of-life vehicle (more than 10 years of use)	Injection molding with a melt temperature of 290 °C (reference material) and 285 °C (reprocessed material), pressure of 80–100 bar, and time cycle of 40.5 s	Short glass fibers (GF)	Findings indicate that mechanical recycling causes fiber breakage, reducing their mechanical strength contribution, although maintaining acceptable characteristics for alternative automotive applications. However, the recycled material still presented a better performance than unreinforced PA66.	<a href="#">Pietrolungo et al. (2020)</a>
PA66 (65 %) + short glass fibers (35 %)	Pellets of a short glass fiber reinforced PA66 (PA66GF35)	Injection molding with a melt temperature of 280 °C and mold temperature of 70 °C	Short glass fibers (GF)	Results provided an understanding of how mechanical recycling and reprocessing affect the fatigue behavior and mechanical properties of glass fiber reinforced PA66. Fatigue strength decreased proportionally with the amount of reprocessed	<a href="#">Bernasconi et al. (2007)</a>

(continued on next page)

Table 3 (continued)

Material	Source	Recycling process	Additives	Main achievements	Reference
Blends of PET/PA containing 0, 25, 50, 75 and 100 % of PA	PET wastes from the production of nonwoven fabrics (NWF) and PA wastes from old tires.	Extrusion with thermal profile = 250-260-270-270 °C	Trans-reaction catalyst using tin(II) 2-ethylhexanoate (approx. 0,1 %)	material, indicating that reprocessing led to fiber shortening during injection molding, reducing material strength and stiffness. Blends containing 25 % and 50 % PET exhibited significant compatibility improvements due to the trans-reactions between PET and PA polymer chains during extrusion, showing the feasibility of recycling PET and PA wastes through polymer blending.	<a href="#">Ferreira et al. (2011)</a>
PA6/66 (Ultramid C40L, BASF), in two different film composition: PE/PE/ad/PA/ad/PE/PE (Film A) and PE/ad/PA/EVOH/PA/ad/PE (Film B)	Multilayer films for meat products packages	Films were grounded, washed, pelletized, dried, and homogenized. Then, new films were produced using a balloon extruder, with a temperature profile = 190-220-230-235-235 °C.	Commercial polyolefin compatibilizer additive with maleic anhydride (MA) (5–7 %)	Films without compatibilizer were non-recyclable. However, the incorporation of the MA-based compatibilizer effectively created a PA-MA-PE copolymer, enhancing adhesion between material interfaces, being a viable approach to enhance the recyclability and mechanical properties of multilayer packaging containing PA. PE-g-MAH improved the interfacial adhesion and the mechanical properties of the regranulated PE/PA blends, while reduced its water absorption, showing the possibility of producing good quality products from immiscible polymer waste.	<a href="#">Turriziani et al. (2024)</a>
PE (80 %) + PA6 (20 %)	Post-consumer waste	Extrusion with thermal profile = 250/240-235-235-230-230 °C	Polyethylene-graft-maleic anhydride (PE-g-MAH) copolymer (1–3 %)	Both thermal stability and mechanical properties of the recycled material were improved with the use of the compatibilizer if compared to the materials with no additives, demonstrating the feasibility of obtaining recycled materials with good properties without the necessity of separating their layers.	<a href="#">Czarnecka-Komorowska et al. (2021)</a>
Co-extruded film of LDPE/LLDPE blend (83 %) + PA6 (15 %) + additives (2 %)	Post-consumer oil pouch	Extrusion with thermal profile = 200-210-220-230 °C	Zinc salt of ethylene methacrylic acid copolymer (Surlyn ionomer); polyethylene grafted maleic anhydride (Fusabond) (5 %)	Significant interactions were observed between the polymers, influenced by blend composition. Some blends demonstrated potential to be reused in other textile applications, contributing to sustainability efforts in the textile industry.	<a href="#">Choudhury et al. (2006)</a>
PA6 + Spandex™ (a kind of polyurethane) + recycled PET at ratios of 100/0, 80/20, 50/50, 20/80 and 0/100	rPET from carbonated beverage bottles; PA6 + Spandex from underwear fabric scraps	Melt-processing of the blends in a torque rheometer at 240 °C.	No additives were used	The compression molded composites from the discarded carpets presented good sound absorption, mechanical properties and water stability, showing potential for transportation and construction industries. Observed enhanced properties with SBR particles without compromising tensile and flexural strength, and improved elastic modulus, flexural strength, and impact resistance with CaCO <sub>3</sub> particles.	<a href="#">Albitres et al. (2017)</a>
PA6 (38 %) + CaCO <sub>3</sub> (40 %) + SBR (12 %) + PP (10 %); or PA6,6 (40 %) + CaCO <sub>3</sub> (40 %) + SBR (12 %) + PP (8 %)	Carpets	Compression between two aluminum sheets and pressed (10 Mpa) at temperatures of 220, 230, 240 and 250 °C for 3 (PA6) and 5 min (PA6,6).	No additives were used	The invention focused on producing a functional	<a href="#">Pan et al. (2016)</a>
Primary components of a conventional carpet: PA	Carpets	Melt blending (extrusion): preferably performed at	Preferably, the process is performed in the absence of		<a href="#">Donald et al. (1994)</a>

(continued on next page)

Table 3 (continued)

Material	Source	Recycling process	Additives	Main achievements	Reference
(to form tufts); polyolefins (such as PP, to form backing); and SBR, which is an adhesive material typically filled with an inorganic filler such as calcium carbonate.		temperatures of about 250–260 °C, pressure of about 350–450 psi, and a shear rate of about 200–400 per sec	a compatibilizer. However, compatibilizers may optionally be added to enhance some properties of the final product.	thermoplastic composition from used carpets, without separating the individual components before recycling (very effective, however expensive and energy-consuming). The obtained composition can partially replace virgin conventional thermoplastic resins.	
Virgin and used PA12 powder + additives (at different %)	Commercial resin	Recycling by Additive Manufacturing (3D printing) - Injection-molding according to standard of ISO 527-2 type 5B	Mechanically milled TPU pellets; aramid short fibers; and graphite powder.	The study satisfactorily proposed an innovative alternative for materials that would be discarded from other processes. The most important observation was that the differences between virgin and recycled PA12 were insignificant for the process, and the additives introduced to PA12 resulted in specimens with more predictable characteristics.	Mägi et al. (2016)

Abbreviations on this Table: CaCO<sub>3</sub> = Calcium carbonate; CF = Carbon fibers; EVOH = Ethylene-vinyl alcohol copolymer; GF = Glass fibers; LDPE = Low-Density Polyethylene; LLDPE = Linear Low-Density Polyethylene; MA = Maleic anhydride; PA = Polyamide; PE = Polyethylene; PE-g-MAH = polyethylene-graft-maleic anhydride; PET = Polyethylene terephthalate; PP = Polypropylene; SBR = Styrene butadiene rubber.

of a material. The findings advocate for a holistic approach to packaging sustainability that integrates LCA with circularity assessments and considers the environmental impacts of the packaged goods. The authors discuss the need for industry collaboration to bridge the gap between theoretical recyclability and actual recycling rates and urge future research into innovative packaging solutions that balance recyclability, resource efficiency, and product protection.

Overall, mechanical recycling of PA encounters significant challenges due to material degradation from heat, moisture, and mechanical shear during reprocessing. These factors, combined with long-term environmental exposure and mixed material compositions, can impact the polymer's properties. To mitigate these issues, additional components such as virgin polymers, fillers, and additives are incorporated to enhance properties. Although compatibilizers can assist in recycling mixed plastics, finding universal solutions remains difficult. Furthermore, the environmental footprint of packaging highlights the need to balance recyclability with effective product protection. Table 3 presents some real-case studies aimed at overcoming these challenges.

### 3.3.2. Overview of the works about mechanical recycling of polyamides

Based on the literature surveyed regarding PA mechanical recycling, Table 3 offers a comprehensive overview of the research in this field, highlighting the materials investigated and the processing methods employed.

The studies summarized in Table 3 illustrate diverse methodologies for the mechanical recycling of PA and PA-containing materials, highlighting a range of challenges, strategies, and results across various fields. These include the effects of repetitive processing (Lozano-Gonzalez et al., 2000; Su et al., 2007), the influence of processing conditions (La Mantia et al., 2002), the recycling of PA with reinforced composites (Bernasconi et al., 2007; Colucci et al., 2015; Pietroluongo et al., 2020), applications in food packaging and post-consumer waste (Albitres et al., 2017; Choudhury et al., 2006; Czarnecka-Komorowska et al., 2021; Ferreira et al., 2011; Turriziani et al., 2024), textile and carpet recycling (Donald et al., 1994; Pan et al., 2016), and advancements in additive manufacturing (Mägi et al., 2016).

In the first group, we can mention works exploring the systematic reprocessing of polyamide samples to verify the effect of a possible repetitive mechanical recycling on their properties. For example, Su et al. (Su et al., 2007) examined the repetitive processing of virgin PA6

through a conventional procedure over 16 cycles. Characterization of both virgin and reprocessed PA6 from each cycle was conducted to assess mechanical and rheological properties, correlating them with the number of processing cycles. Changes in chemical structure, molecular weight, molecular weight distribution, and crystalline behavior were analyzed after each cycle. Results showed that, despite decreases in molecular weight and increases in molecular weight distribution due to reduced melt viscosity, the chemical structure of PA6 remained unchanged based on FTIR spectra. DSC thermal analysis revealed altered crystallization behavior with reprocessing cycles, leading to smaller and imperfect crystallites and an increased crystallization rate. Considering the mechanical properties, an increase in tensile yield stress and flexural strength with each processing cycle was observed. However, Izod impact strength decreased over successive cycles, indicating a transition from soft and tough to hard and brittle properties.

On the same theme, Lozano-Gonzalez et al. (Lozano-Gonzalez et al., 2000) investigated the impact of multiple recycling cycles of PA6 on its physical and mechanical properties and morphology. Virgin PA6 was processed in an injection molding machine, evaluated, and then granulated in pellets, dried, and processed again. The PA6 underwent 10 recycling cycles, and each injection cycle was analyzed to understand the potential loss of properties over successive recycling rounds. SEM and Optical microscopy were employed to assess the material's morphology, while changes in molecular weight were determined using gel permeation chromatography. No significant changes were noted in the material properties up to the eighth cycle. However, between the 10 cycles of injection and the virgin material, a 10–15 % deviation in properties was observed, except for elongation, which exhibited a gradual 70 % decrease by the tenth injection cycle. SEM images at 5000× magnification revealed that the spherulite size decreases with increasing cycles of nylon-6 injection. This reduction was attributed to unmelted particles formed from polymer degradation, acting as nucleation agents that promote small crystal formation and consequently elevate the crystallization temperature. Therefore, as the number of injection cycles increases, spherulite size decreases, revealing imperfections in the crystalline regions.

Both studies (Lozano-Gonzalez et al., 2000; Su et al., 2007) highlight the cumulative effects of repetitive processing on PA6, revealing changes in molecular characteristics, crystalline structure, and mechanical behavior over multiple injection molding cycles. These findings

provide crucial insights into the limitations and durability of PA6 during multiple recycling processes, offering valuable information for sustainable material management practices.

La Mantia et al. (La Mantia et al., 2002) also followed the same concept of reprocessing commercial polyamide resin. However, unlike the last two authors, they also evaluated the effect of humidity on the quality of the recycled PA6 samples. They compared the performance of dry and wet samples during their mechanical recycling, alongside investigating the impact of utilizing an antioxidant in the wet condition. The material was processed up to five times to mimic the recycling process. Extrusion tests were conducted on dry samples (subjected to vacuum at 120 °C for 24 h) and wet samples (exposed to a humid room for 120 h to ensure complete humidification). After processing, thermal, rheological, and mechanical analyses were performed on the obtained material. The findings indicated that repetitive processing of PA6 could yield secondary material with favorable properties if a meticulous drying step precedes the melt operation. Under these conditions, slight changes were observed in rheological and mechanical properties with an increase in the number of processing steps. Conversely, reprocessing wet materials resulted in a significant reduction in molecular weight due to hydrolytic chain scission. However, using an additive capable of removing water facilitated the recycling of PA under wet conditions, providing a recycled material that exhibited better properties than the ones obtained in dry conditions, even after numerous reprocessing steps.

In another approach, studies evaluated the recycling of PA reinforced or mixed with other materials. For example, Colucci and coauthors (Colucci et al., 2015) investigated the mechanical recycling of polymer composites based on PA66 reinforced with short carbon fibers after artificial aging – combining UV radiation, humidity and temperature to simulate common outdoor conditions – targeting applications in the automotive sector. The study focused on comparing the mechanical behavior and microstructure of the composites before and after mechanical recycling, being the recycled composites obtained through re-granulation of aged samples, followed by remelting and re-injection. The mechanical, thermal, and morphological investigation results revealed that Young's modulus and tensile strength remained unchanged after recycling, despite a reduction in average fiber length during grinding, indicating robust mechanical stability through the process. SEM analysis revealed a weakening of interfacial bonds between fibers and matrix, which paradoxically improved toughness. Fiber alignment in the molding direction was well-maintained throughout recycling. The mechanical properties of the recycled composites were comparable to other materials used in vehicles, making them suitable for semi-structural applications in the automotive industry.

Bernasconi et al. (Bernasconi et al., 2007), in turn, investigated the effects of mechanical recycling of PA66 reinforced with short glass fiber (GF) through granulation and subsequent injection molding. Focus was on fatigue behavior due to cyclic loading, critical for designing durable components. The investigation focused on varying ratios of virgin to recycled materials (0 %, 25 %, 50 %, and 100 % recycled). The samples underwent characterization concerning GF length distribution, along with tensile and fatigue mechanical testing. Findings highlighted reprocessing led to fiber shortening during injection molding, reducing material strength and stiffness. Through comprehensive testing, including tensile and fatigue tests across materials with different proportions of recycled content, it was confirmed that fatigue strength decreased proportionally with the amount of reprocessed material, similar to tensile strength reductions. Additionally, the study evaluated moisture's impact on virgin material, showing reduced stiffness and fatigue strength but increased ductility upon water absorption. Overall, the work ensured the practical application of recycled materials in real-world scenarios despite the challenges.

Similarly, Pietrolungo et al. (Pietrolungo et al., 2020) investigated automotive residues (radiator parts over 10 years old) using PA66 reinforced with short GF. The feasibility and implications of mechanically recycling this component were evaluated. Through three cycles of

pelletization and injection molding, the research compared the recycled material's microstructural, rheological, and mechanical properties with those of the original composite. Findings indicate that mechanical recycling causes fiber breakage, reducing their mechanical strength contribution, although maintaining acceptable characteristics for alternative automotive applications. While the mechanical properties degrade progressively with each reprocessing cycle, mainly due to fiber length reduction during milling and molding, the recycled material still performs better than unreinforced PA66. Future improvements could focus on optimizing molding processes and potentially compounding with virgin materials to further enhance the recycled composite's properties. The authors highlighted mechanical recycling as a viable solution for diverting composite materials from landfills, aligning with EU regulations on vehicle material reuse (reuse of 95 % in weight of each vehicle).

Regarding food packaging, Turriziani et al. (Turriziani et al., 2024) evaluated the mechanical recycling of multilayer flexible films used for meat product packages. In their work, the authors addressed the challenge of recycling this type of package, focusing on films composed mainly of PE and PA in two different compositions (ad = adhesive): PE/PE/ad/PA/ad/PE/PE (Film A) and PE/ad/PA/EVOH/PA/ad/PE (Film B). Initially, the authors applied the RecyClass tool to assess the theoretical recyclability of the two multilayer films, showing that films without compatibilizer were non-recyclable. However, extrusion recycling experiments demonstrated that incorporating a commercial MA-based compatibilizer (at concentrations of 5 % and 7 %) effectively created a PA-MA-PE copolymer, enhancing adhesion between material interfaces as observed in microscopy images. While adding compatibilizer stabilized PE's melting temperature, it altered PA's melting temperature in Film-A. Film-A with compatibilizer also exhibited lower overall crystallinity and significant improvements in tensile strength and elongation at break, particularly in the transverse direction. These findings highlight the efficacy of PA-MA-PE compatibilization as a viable approach to enhance the recyclability and mechanical properties of multilayer packaging for meat products. However, further optimization is still necessary to maximize their performance.

Ferreira et al. (Ferreira et al., 2011), following the idea of promoting the recycling of two immiscible materials, investigated a complex polymer blend by recycling PET with PA fibers. Reactive extrusion was explored as a sustainable approach to blending these materials into new polymeric blends using a trans-reaction catalyst (tin(II) 2-ethyl hexanoate). This approach enabled chemical interactions between PET and PA chains during processing, improving compatibility in blends containing 25 % and 50 % PET. Despite initial degradation in PET from blanket production processes, the trans-reactions led to the formation of copolymers. Although often associated with mechanical recycling, this approach may also be considered a form of chemical recycling due to the reactive nature of the process. The study demonstrated a viable and environmentally beneficial solution for recycling PET and PA waste through reactive compatibilization, despite the potential for thermal and hydrolytic degradation of these polymers during reprocessing.

Other studies evaluated the mechanical recycling of polyamides present in post-consumer wastes. Choudhury et al. (Choudhury et al., 2006), for example, highlighted in their investigation the significant role of compatibilizers in improving the properties of recycled polymer blends from oil pouches and also avoiding the need for the challenging and costly task of separating polymers before recycling. Two specific compatibilizers were investigated: Zinc salt of ethylene methacrylic acid copolymer and polyethylene grafted maleic anhydride. The properties of the recycled material were assessed through a battery of analytical techniques, including FT-IR, melt flow index, SEM, DSC, XRD, and mechanical property testing. The results revealed notable enhancements in both mechanical and thermal properties when utilizing compatibilizers compared to recycled material lacking such additives.

Still on the topic of recycling post-consumer waste with additives, Czarnecka-Komorowska et al. (Czarnecka-Komorowska et al., 2021)

synthesized a re-granulated (R) PE + PA product from post-consumer waste material, utilizing polyethylene-maleic anhydride (PE-g-MAH) as a compatibilizer. The material underwent processing via screw extrusion, and various analyses were conducted to assess the compatibility effect of PE-g-MAH as a modifier in R-PE/R-PA blends, including SEM, density, water absorption, melt mass-flow rate (MFR), melt rheology, FT-IR, DSC, thermogravimetry (TGA), and mechanical testing (hardness, Young's modulus, ultimate tensile strength, tensile stress at break, and elongation at break). The blend comprising R-PE/R-PA/-MAH, presenting a higher concentration of compatibilizer, exhibited increased hardness, rigidity, and tensile strength correlated with the rise in crystallinity. Additionally, the addition of PE-g-MAH to the R-PE/R-PA waste mixture favored interfacial interactions and compatibility between R-PE and R-PA, reducing the size of polyamide particles and decreasing water absorption of the blends. The findings demonstrate the feasibility of producing high-quality re-granulated products with good properties from immiscible polymer residues for industrial applications.

Another essential niche involving the mechanical recycling of polyamides is that which considers the polyamide in carpets and fabrics, which are often disposed of in landfills, leading to environmental pollution and the waste of valuable petroleum-based polymers. Carpet recycling was the theme of an invention (US patent #: US5294384A) (Donald et al., 1994), which introduced a process for creating a thermoplastic composition from carpet samples without the need to separate the carpet into its constituent parts, namely: tufts made from PA; a backing composed of polyolefins like polypropylene; and an adhesive material such as styrene-butadiene rubber (SBR) filled with inorganic filler like calcium carbonate. Recycling such multi-component products poses significant challenges due to their diverse chemical and physical characteristics. Previous recycling attempts have been limited in utility and often restricted to specific applications where composite materials are suitable. Alternatively, some methods involve separating individual components, which, while effective, are very expensive and energy-consuming, diminishing the environmental benefits of recycling. The invention addresses these challenges by offering a method to process used carpet into a functional thermoplastic composition by blending unseparated carpet material under controlled temperature, pressure, and intensive mixing conditions. This composition exhibits properties akin to virgin thermoplastics, enabling its use in various applications. Thus, the invention provides a sustainable solution for repurposing conventional carpeting materials into versatile thermoplastic compositions.

In the same subject, Pan et al. (Pan et al., 2016) addressed the challenge of handling discarded carpets, developing a novel method for reusing them focused on creating compression-molded composites from discarded PA6/PA66 carpets. The authors observed enhanced properties with SBR particles without compromising tensile and flexural strength and improved elastic modulus, flexural strength, and impact resistance with calcium-carbonate particles. The obtained material demonstrated superior performance over jute/PP composites in sound absorption, flexural strength, elastic modulus, impact resistance, and water stability. Overall, the development of compression-molded carpet composites with superior mechanical properties and sound absorption capabilities offers a potential application in transportation and construction industries, opening the way for effectively reusing discarded carpets and reducing environmental impact.

Albitres et al. (Albitres et al., 2017), in turn, focused on recycling textile industry waste, specifically underwear fabric scraps composed of PA6 and Spandex™ (a kind of polyurethane), along with recycled PET, into melt-extrusion blends at varying proportions. Using analytical techniques like NMR, DSC, TGA, SEM and dynamic mechanical analysis (DMA), the researchers investigated the molecular mobility, thermal properties, morphology, and mechanical characteristics of the blends. Results indicated significant interaction between the polymers, influenced by blend composition, resulting in changes in crystallization

behavior, thermal stability, and mechanical properties. The blends demonstrated potential to be reused in other textile applications, contributing to sustainability efforts in this industry.

Lastly, Mägi et al. (Mägi et al., 2016) explored ways to use of leftover PA12 powder from Selective Laser Sintering as the base material for creating enhanced filament blends intended for Fused Deposition Modeling (FDM) technology in Additive Manufacturing (AM), or 3D printing. The primary aim was to formulate materials to improve FDM-printed hand prostheses' usability and functionality. Another core concept of this study was to promote environmental sustainability, which was accomplished by repurposing material that would otherwise be discarded into new raw material for alternative processes. Test specimens were produced using PA12 in both its virgin and recycled forms and blends of PA with thermoplastic polyurethane (TPU), aramid, or graphite. These specimens were then tested for their mechanical properties using a micro-injection molding machine. The study investigates the differences in mechanical characteristics among these various material blends. Surprisingly, the study found that the differences between virgin and recycled PA12 were insignificant, and the additives introduced to PA12 resulted in specimens with predictable characteristics, marking a significant accomplishment.

Regardless of its application – be it in carpets, engineering materials, food packaging, or commercial resin – mechanical recycling emerges as a viable method for reusing PA. It is important to stress, however, that effective recycling relies on proper separation of PA from other materials when feasible and consideration of factors such as moisture content and the number of extrusion cycles to prevent degradation of polymer quality. Overall, the studies here presented underscore the potential of mechanical recycling to enhance sustainability in various industrial sectors. Nevertheless, it is important to note that comprehensive Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) data remain limited in the current literature. Future research should address this gap by evaluating the full environmental and economic impacts of reusing PA-based materials, thereby supporting their broader implementation in industry.

#### 4. Conclusions

PA are crucial in various industries due to their versatility, with applications ranging from engineering materials and food packaging to textiles. As the focus on circular economy principles intensifies, emphasizing waste reduction, resource efficiency, and the extension of product life cycles, mechanical recycling of PA emerges as a vital strategy for enhancing sustainability and reducing environmental impact. Despite its potential, mechanical recycling of PA presents several challenges, including maintaining material quality through multiple recycling cycles, effectively separating PA from other materials, and managing moisture content and degradation issues during processing. The reviewed studies highlighted progress and obstacles in this field, showing that while recycling technologies can be optimized, significant efforts are still required to address these challenges. Future research should focus on developing advanced recycling techniques, improving the compatibility of recycled materials, and exploring innovative applications to realize the potential of PA recycling fully. By overcoming these hurdles, we can advance towards a more sustainable approach to material management, contributing to a robust circular economy and reducing reliance on virgin resources.

#### Authors contribution statement (CRediT)

**Nanci Castanha:** Conceptualization, Data curation, Investigation, Project administration, Writing – original draft, Writing – review & editing. **Fiorella Balardin Hellmeister Dantas:** Project administration, Supervision, Resources, Writing – review & editing. **Luís Marangoni Júnior:** Conceptualization, Investigation, Project administration, Supervision, Writing – review & editing.

## Declaration of interests

The authors have nothing to declare.

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## Data availability

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

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