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POLIMERY

PET composites and their applications in the face of green chemistry challenges – an overview

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Abstract: The review discusses the recycling of PET packaging, highlighting its significance in the circular economy. It presents methods for processing the recovered material and its potential applications in various sectors of the economy. The importance of the 6R principle in integrating the economy and promoting sustainable development is also emphasized.

Keywords: recycling, green chemistry, circular economy, composites, PET.

Kompozyty PET i ich zastosowanie w obliczu wyzwań zielonej chemii – przegląd literaturowy

Streszczenie: W artykule omówiono recykling opakowań PET, podkreślając jego znaczenie w gospodarce obiegu zamkniętego. Przedstawiono metody przetwórstwa odzyskanego materiału i jego potencjalne zastosowania w różnych sektorach gospodarki. Wykazano znaczenie zasady 6R w integracji gospodarki i promowaniu zrównoważonego rozwoju.

Słowa klucze: recykling, zielona chemia, gospodarka obiegu zamkniętego, kompozyty, PET.

Poly(ethylene terephthalate) (PET) was invented in 1941 by British chemists John Rex Whinfield and James Tennant Dickson and has since become one of the most widely used polymers [1]. This is due to its broad spec-

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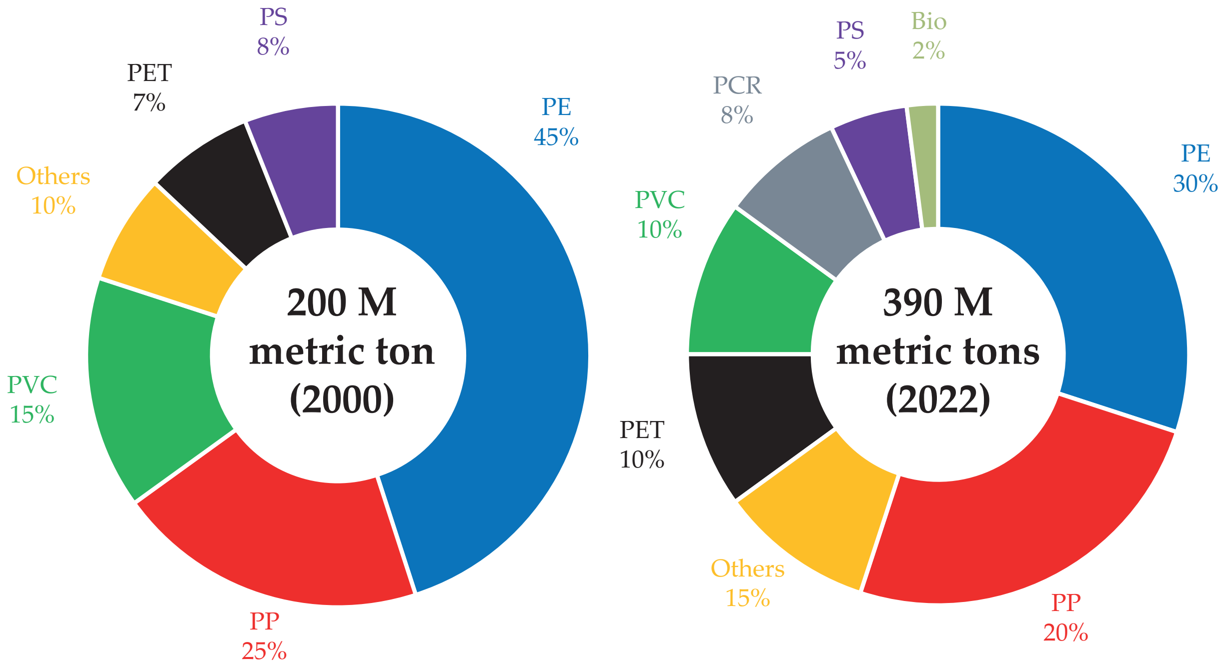

Fig. 1. Polymer production structure over the years

trum of applications. PET gained popularity in the 1970s as a material for producing beverage bottles. Further research revealed its excellent mechanical properties, significantly expanding its range of applications and usage potential. PET has a tensile strength ranging from 50 to 80 MPa [2, 3], making it suitable for producing bottles and textile fibers. Its elastic modulus ranges from 2.1 to 2.8 GPa and Shore's hardness ranges from 75 to 80 [3], enabling the production of various structural components.

Reports published by various institutions [4, 5] were used to prepare Figure 1, which illustrates the changes in global polymer production from 2000 to 2022. During this period, production almost doubled, increasing from 200 million tons to 390 million tons. The graph includes polymers such as polyethylene (PE), including LDPE, HDPE, and LLDPE; polypropylene (PP); polyvinyl chloride (PVC); polyethylene terephthalate (PET); polystyrene (PS); post-consumer recycled plastics (PCR); biopolymers (Bio); and others (e.g., polyurethanes, polycarbonates, and polyamides). The share of PET in production increased from about 7% to about 10%. Therefore, it is crucial to further improve the efficiency of PET recycling processes and find new applications for recycled PET (rPET).

Recycling PET primarily involves mechanical and chemical recycling. Mechanical recycling significantly reduces PET's molecular weight, impacting its mechanical properties. However, the effect on properties such as tensile strength and impact resistance is relatively minor, making mechanical recycling a cost-effective method for reusing PET. Studies have shown that blending virgin PET with up to 20% recycled polymer retains properties similar to virgin PET, suggesting an economical and environmentally friendly recycling strategy. Additionally, research indicates that PET's crystallinity rises with increased re-cycling cycles, potentially influencing its processing and application in products. However, the reduction in molecular weight may negatively affect stretch-forming processes due to a loss of mixture viscosity [6].

Chemical recycling enables the recovery of petrochemical components from PET waste for reuse in producing other synthetic chemicals [7]. This method breaks down PET into monomers through chemical reactions, which are then reused as raw materials for synthesis. The primary advantage of chemical recycling is the absence of material degradation. However, this method has drawbacks, including a complex technological process, lengthy timescales, and high costs [8]. Additionally, its environmental neutrality is questioned due to emissions and waste generated during production and equipment operation. Though not widely accepted, there are ongoing discussions on this issue [9]. Hence, the recycling process should be as straightforward as possible. Mechanical recycling is characterized by simple technology and low cost. It involves selecting, washing, and grinding waste materials into flakes. After a quick drying process, the flakes are reprocessed via extrusion or injection molding [10, 11]. Economic viability and environmental friendliness make mechanical recycling the most popular method for recovering PET. Nevertheless, recycled polyesters have lower strength compared to virgin materials, posing challenges to the use of 100% recycled content [12].

Recycling and reprocessing reduce material viscosity and average molecular weight, potentially impairing final mechanical properties such as tensile strength and impact resistance [6]. Macrostructural changes in PET during mechanical recycling via extrusion, such as ther-

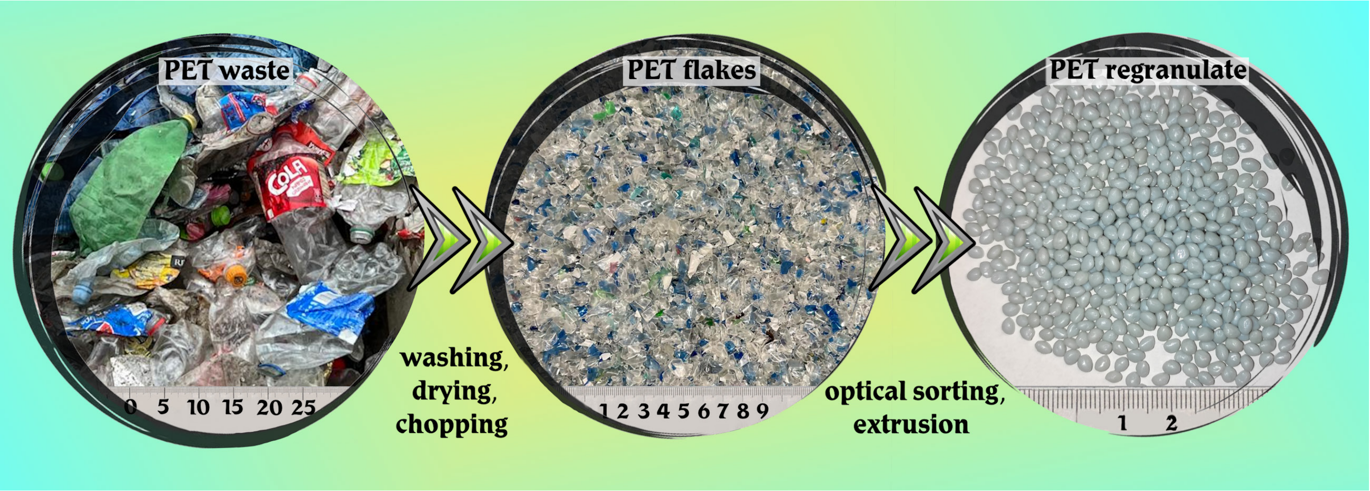

Fig. 2. Recycling process of PET

mal oxidation of the polymer, lead to side-group modifications and macromolecular structure alterations (chain scission, chain elongation, and cross-linking) [13]. These structural changes limit rPET's applications. To meet quality standards, adding virgin PET to rPET at a ratio of 30/70% (rPET/PET) is necessary to ensure acceptable mechanical properties [14].

An alternative approach to improving rPET properties is incorporating dispersed reinforcement fibers during extrusion. Glass fibers (GF) are typically used due to their excellent mechanical and physical properties and low cost. Furthermore, glass fibers increase the mixture's viscosity - a drawback that can become an advantage in recycled polymers, given that mechanical recycling tends to reduce this property [15].

In recent years, researchers have explored using recycled PET as a matrix for fiber-reinforced composites [16–19]. Mechanical properties generally improve with increasing glass fiber content [16]. The excellent properties of PET/rPET+GF mixtures and the lack of reusability for colored and contaminated waste in the food industry make this material suitable for technical applications, such as in the automotive sector [16, 18, 20–22].

Recycling PET into rPET involves several steps, as schematically illustrated in Figure 2 [23]. Collected PET waste is compressed into blocks, which are then unpacked and sorted by color and type. Other materials, such as paper, metal, and glass, are separated by various methods, and labels and caps are removed. Bottles are washed in alkaline solutions at high temperatures to eliminate contaminants such as food residues and oils [24]. The cleaned PET (Figure 2) is then cut, shredded, and further purified using optical sorters to remove non-PET materials based on spectral differences. This process often results in the rejection of some PET flakes as waste due to contamination with adhesives and other polymers like polypropylene. These materials, while unsuitable for food-contact applications, may hold value in the construction industry. PET flakes are melted and formed into granules, known as regrind, which are used in the plastics industry to produce finished products. This material serves as an input substrate for our research.

Eliminating non-PET materials during PET packaging recycling presents several challenges. Residues from the recycling process itself, such as detergents and alkalis, may become additional contaminants in the final product [25]. High-temperature processing can degrade PET, creating new compounds that hinder the separation of non-PET materials. Contaminants like oils and sugars from food residues may react with these degradation products or other residues, leading to further contamination.

Recycled PET differs from virgin PET, particularly in terms of potential migration risks into food products. rPET may contain unintentionally added substances (NIAS) from the recycling process, including degradation products and contaminants absent in virgin PET. These additional compounds raise concerns about potential migration into food, as their safety may not have been thoroughly assessed [25]. While closed-loop recycling is a goal for many facilities, achieving it is limited by the inherent degradation of the polymer, necessitating the addition of virgin PET to maintain material quality over time [25–27].

SCIENTOMETRIC ANALYSIS

A scientometric analysis was conducted to identify key scientific trends and areas requiring further exploration [28–32], using data visualization from library catalogs such as Scopus and Web of Science [32, 33], which cover a broad range of scientific publications. The database search was performed on literature resources current as of December 2024, using keywords such as "recycling," "green chemistry," "circular economy," "plastic wastes," "polymer composites," and "PET." This analysis revealed trends and gaps in the literature. The data were analyzed using VOS viewer software to construct and visualize bibliometric networks, highlighting keyword co-occurrence and relationships [34]. Figure 3, developed based on this analysis, demonstrates that studies on the mechani-

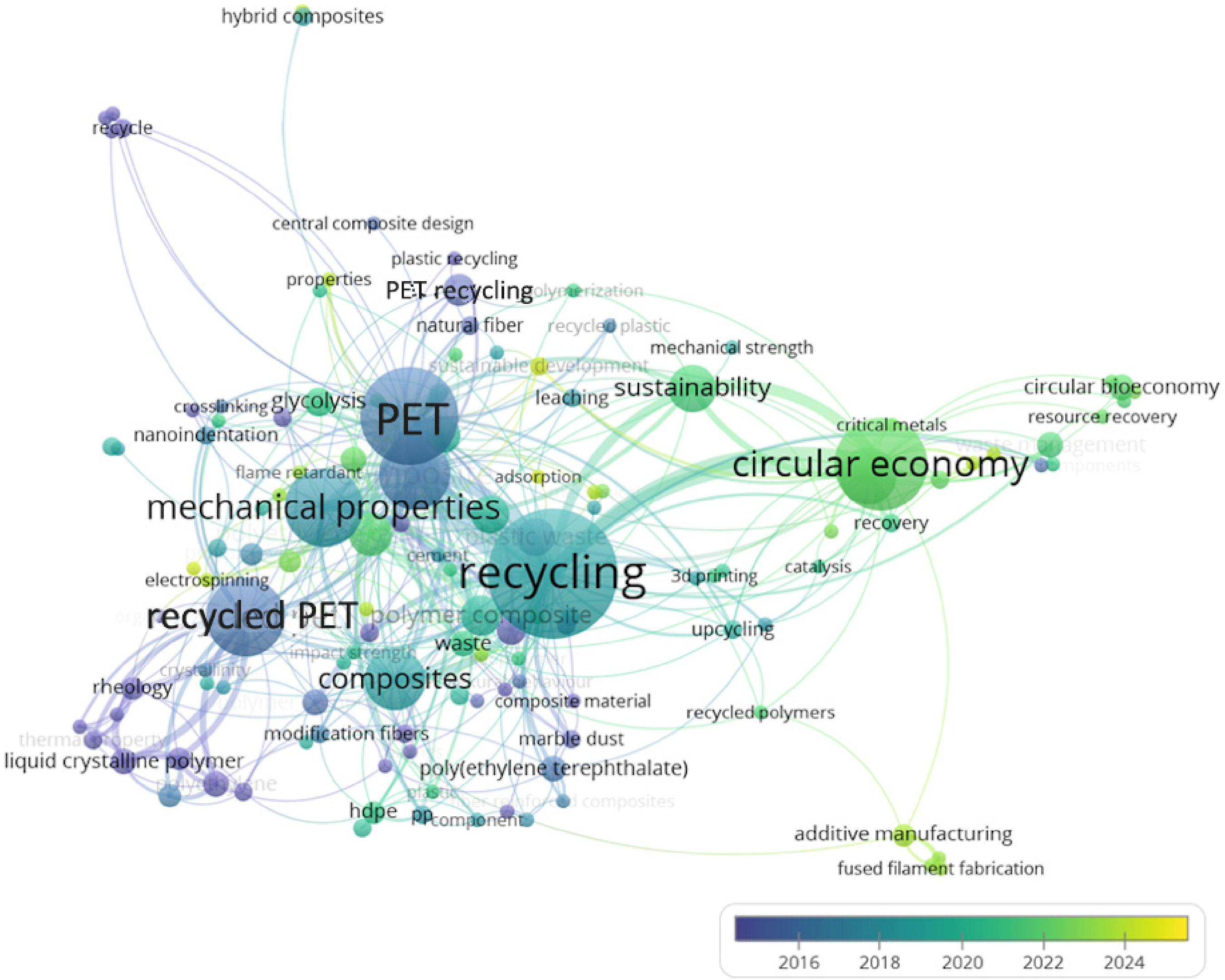

Fig. 3. Incidence and relationship of keywords created using VOS viewer, additionally showing the publication date (accessed on 12.2024)

cal properties of rPET + GF are less explored compared to topics such as recycling and the utilization of reinforced polymers, indicating the need for further research in this area. This visualization also helps identify research trends and guides future studies through the selection of appropriate keywords.

To identify clusters for Figure 3 among over 900 author-provided keywords in separate publications, those appearing at least twice were selected, reducing the number of analyzed keywords to 130. This indicates significant diversity in the topics. Keywords that were not thematically connected were excluded from the visualization. The presence of many weakly connected keywords suggests their rare occurrence, being cited only a few times alongside other analyzed terms from various texts. Furthermore, the color of individual clusters indicates the year when a specific keyword appeared in publications. The absence of yellow colors suggests a decline in scientific interest in the given topic.

The presented visualization not only helped identify trends but also guided future authors in selecting keywords to locate published data on specific topics. Topics related to the mechanical properties of rPET + GF have been explored less in recent years compared to recycling and the use of reinforced polymers. This analysis highlights the need for further research in this specific thematic area.

RPET PROCESSING

During the recycling process, PET undergoes a loss of its thermal and mechanical properties. To minimize this effect, advanced technologies for chemical structure modification and material property enhancement are employed. Among these, solid-state polycondensation (SSP) and liquid-state polycondensation (LSP) are particularly significant, as they increase the average molecular weight and improve the quality of recycled PET [35].

The SSP process is conducted at temperatures below the polymer's melting point in an inert gas atmosphere. It involves heating shredded polymer followed by crystallization. During heating, the terminal acid and hydroxyl

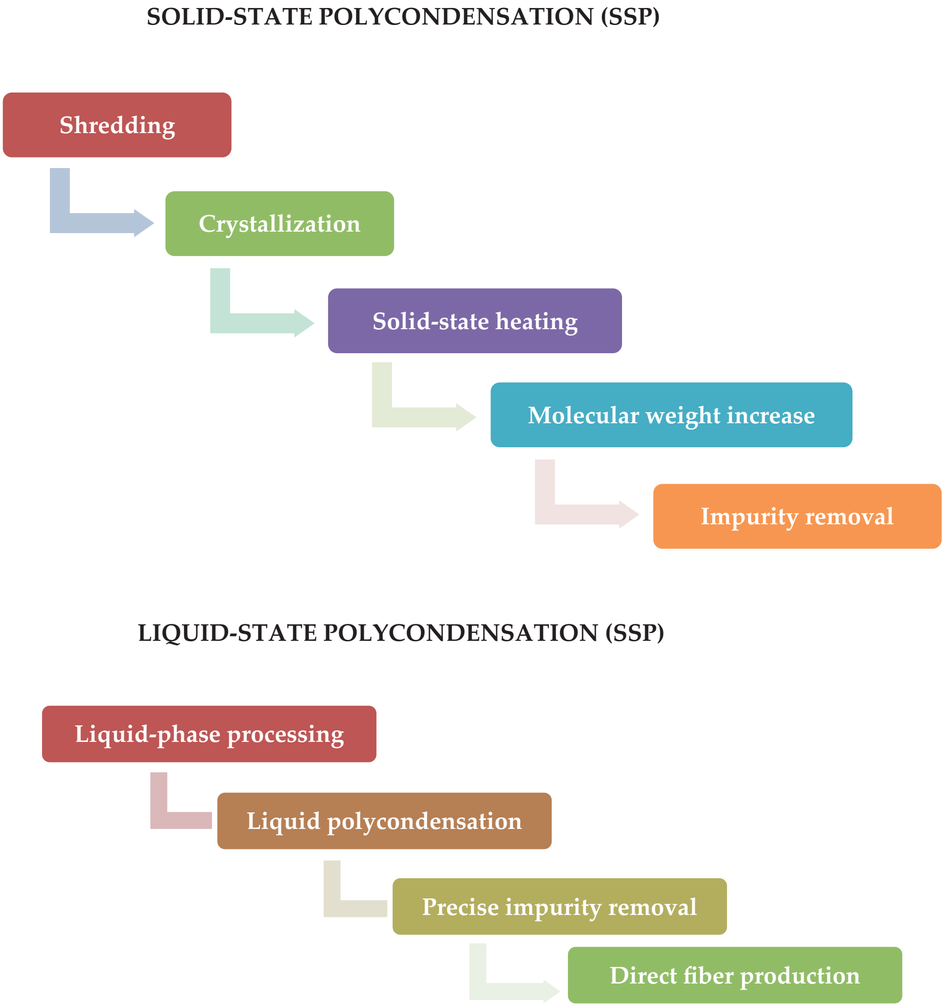

Fig. 4. Flowchart comparing SSP and LSP processes

groups react, increasing the polymer's molecular weight. By utilizing lower temperatures, the formation of by-products is reduced [36–38]. This process does not require toxic solvents, making it environmentally friendly. SSP improves the mechanical strength and thermal resistance of the material, enabling its use in the production of synthetic fibers and food packaging [38]. Additionally, SSP effectively removes impurities, such as residual monomers, making it a common choice for industrial-scale PET recycling.

Studies described in [16] demonstrate the impact of the SSP process on the properties of PET recyclate reinforced with glass fibers (GF). It was found that SSP significantly increases the average molecular weight and enhances the strength and stiffness of rPET/GF composites. These improvements were linked to better morphological structure, which translated into superior mechanical properties, including tensile strength and hardness [16].

Research [39] further confirms the beneficial effects of SSP on the mechanical properties of PET composites. Enhanced material properties have allowed broader applications in the textile and packaging industries.

Unlike SSP, the LSP process is conducted in the liquid phase. Current technology allows polymer processing directly during spinning, eliminating additional reaction stages such as pelletizing or screw extrusion. This reduces energy consumption and shortens production time, while also increasing control over the molecular structure of the resulting material. LSP produces a material with a higher average molecular weight and more uniform properties. It enables faster polycondensation and precise impurity removal, giving rPET properties similar to virgin material [39]. The LSP method allows the production of high-strength polyester fibers, which are widely used in the textile industry for fabrics and mechanically resistant materials, as well as in the automotive sector. It is also used in modifying PET regranulate, improving its suitability for manufacturing food-contact packaging [39, 40].

The flowcharts in Figure 4 illustrate the progression of these processes. SSP requires temperatures below the melting point and prolonged periods to remove by-products. It enhances the polymer's mechanical and chemical properties [39].

LSP, on the other hand, operates at high temperatures. Conducting reactions in the liquid phase ensures rapid molecular weight growth. However, it demands meticulous control of the reaction process to avoid polymer degradation [39].

Table 1. Effect of fiber type on PET/rPET properties

Fiber type	Tensile strength MPa	Young modulus GPa	Melting temperature, °C	Electrical conductivity	Density g/cm^3
Glass	2000–4000	70–90	1200–1450	Insulator	2.5–2.7
Carbon	3000–6000	120–250	Does not melt	Conductor	1.6–1.9
Basalt	2000–4800	80–110	1200–1450	Insulator	2.7–2.9
Aramid	3000–4500	70–120	Does not melt	Insulator	1.4

Studies presented in [41] show that LSP achieves better impurity removal compared to SSP, resulting in significantly higher-quality recyclate [41]. Molecular structure analysis confirmed that LSP yields a more homogeneous PET structure, contributing to improved mechanical properties [41]. Furthermore, [42] compared the efficiency of both processes, concluding that LSP is more effective in enhancing the usability parameters of fibers, such as elasticity and tensile strength [42].

To improve rPET properties, various techniques are increasingly used to enrich its structure with additional components. Modifications include adding nanoparticles like silica (SiO_2) or alumina (Al_2O_3), reinforcing the material with fibers, fly ash, or other mineral additives, creating blends, or extending polymer chains.

For example, the studies described in [43] showed that the introduction of SiO_2 nanoparticles into PET significantly increases the UV resistance. This modification also improves the tensile strength and thermal stability, making the material more resistant to long-term degradation [43]. However, maintaining satisfactory crack resistance with high filler content poses a challenge, as excessive fillers can reduce the material's impact energy absorption. A promising solution involves incorporating elastomers into composites to improve impact resistance and elongation at break. SiO_2 nanoparticles are also used as surface modifiers in PET textiles, improving adhesion between materials by increasing the surface roughness and wettability of PET fibers.

Another popular modification method is adding fly ash to composites. This reduces shrinkage and improves the elastic modulus of the processed material. Studies [44] showed that incorporating fly ash into PET increases its stiffness, making it suitable for producing structural components in construction [44]. Composites with this additive also exhibit improved mechanical properties, such as flexural and compressive strength. Alkali-activated fly ash demonstrates better acid resistance, such as against sulfuric acid, making it a promising component for eco-friendly building composites [44, 45].

Incorporating glass or carbon fibers is another promising method for enhancing the mechanical properties of PET composites. For example, studies described in [46] indicate that adding glass fibers to PET recyclate increases the composite's tensile strength and impact resistance [46]. Other fibers, such as basalt and aramid, also offer notable benefits. Table 1, based on [47, 48], presents comparative parameters of various fibers for PET/rPET reinforcement.

Glass fibers are resistant to acids and bases at moderate temperatures and are available in various lengths and diameters. As additives in composites, they can improve flexural strength, increase impact resistance, and reduce deformation. They also reduce processing shrinkage, enhancing the dimensional precision of products [46, 49]. Additionally, glass fibers enhance thermal stability and decrease vapor permeability, which is particularly important for food packaging, protecting products from moisture. These modifications expand the application range of recycled PET, enhancing its competitiveness against traditional fossil-based polymer materials.

Carbon fibers, with their unique properties, are widely used fillers for PET composites. They improve tensile strength, hardness, and Young modulus. They also accelerate PET crystallization and increase its melting temperature. Various carbon fiber modifications are employed to enhance adhesion with the PET matrix [50, 51]. These fibers are important in sustainability efforts, as PET composites with carbon fibers can be recycled, helping to reduce waste generation [52].

Another method for modifying recycled PET is chain extension, usually achieved using chain extenders. These compounds increase the average molecular weight by joining short polymer chains. Epoxy chain extenders positively impact polycondensation reactions, improving PET's high-temperature resistance, viscosity, and processing efficiency, thereby broadening its applications across industries [42, 53]. Alternatively, introducing carbon fibers to PET can yield highly rigid composites, though this process is costly and complex. The choice of methods depends on the intended application and available technological resources.

APPLICATION OF PET/RPET COMPOSITES

PET and rPET composites are playing an increasingly important role in various engineering branches. This is due to their unique mechanical, chemical and thermal properties, which make them competitive with other materials. Figure 5 shows the most common examples of applications of these composites in various engineering sectors.

In the automotive industry, PET and rPET composites are widely used due to their lightweight, strength, and corrosion resistance. These materials are employed in the production of various car components, including both interior and exterior parts. PET and rPET are used in door

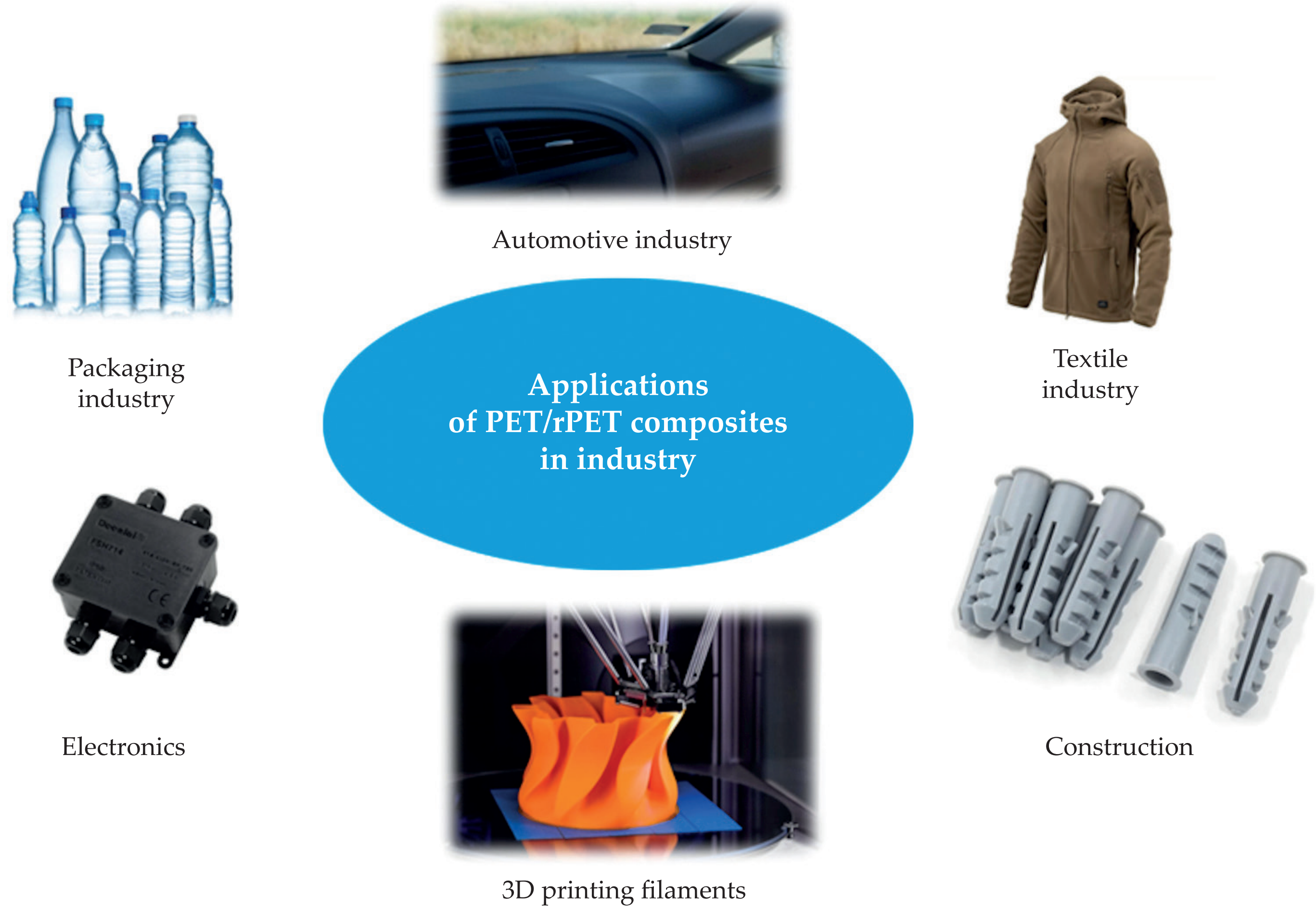

Fig. 5. Examples of PET/rPET composites applications

panels, dashboards, and decorative interior elements. These materials exhibit high mechanical strength and abrasion resistance. For example, door panels made from PET composites can withstand loads of approximately 1500 N while maintaining low weight. Noteworthy are the studies conducted by Karthik's team, which used glass-fiber-reinforced rPET to produce protective straps serving as structural frames for mounting vinyl covers. The resulting components met all automotive industry requirements [54]. PET and rPET composites are also used in the production of exterior automotive parts, such as bumpers, engine covers, and wheel arches. Using composites for these components reduces vehicle weight, leading to lower fuel consumption and CO_2 emissions. For instance, bumpers made from rPET can be 20–30% lighter compared to traditional materials [55]. Another major application area for PET polymers is construction. PET and rPET composites are used to produce various structural and finishing elements. Their high mechanical strength, corrosion resistance, and excellent thermal and acoustic insulation properties make them ideal for this sector. Examples include composite panels made from PET and rPET, which are used in roofing, walls, and floors. These panels exhibit high flexural strength (approximately 100 MPa) and low thermal conductivity 0.22 W/(m·K) [57]. Another example is building façade anchors developed by the team at Cracow University of Technology [57, 58].

PET and rPET composites are also used to produce structural pipes and profiles. Due to their light weight and mechanical strength, these pipes can be used for water transport and as structural elements. The tensile strength of such pipes is about 60 MPa [59]. In recent years, significant research has focused on the reinforcement of rPET fibers with various materials to reduce production costs while promoting environmental sustainability. Kim *et al.* analyzed the use of rPET fibers for reinforcing concrete. Their studies showed a reduction in compressive strength and modulus of elasticity compared to traditional concrete [60]. Fraternali et al. optimized industrially produced rPET fibers with different profiles and properties. They showed that the use of PET monofilaments (at a fiber volume fraction of 1% and a water-to-cement ratio of 0.53) increased the compressive and flexural strength. Concrete reinforced with rPET fibers showed an increase in compressive strength by 22–35% compared to unreinforced concrete. These studies have shown that rPET fiber reinforcement is an effective method for increasing concrete compressive strength, tensile strength, high temperature resistance and ductility [61].

Composites are also used as insulating materials. For example, the team led by Patnaik conducted research on insulating materials made from sheep wool waste and rPET fibers for use in the construction industry. The researchers created samples of pure wool, pure rPET, and their 50/50 blend, which were evaluated for thermal insulation, acoustic properties, moisture absorption, and fire resistance. Wool and rPET samples proved to be effective thermal insulators, while their combination exhibited good thermal and acoustic insulation properties, making them suitable for soundproofing and thermal insulation applications. The materials were also subjected to biodegradation tests to assess their environmental impact. The rPET/wool blends showed biodegradation levels of 60–70% within 50 days, compared to 80–85% for pure wool and 30% for pure rPET. The results suggest that samples made from wool and rPET waste could serve as eco-friendly alternatives to traditional insulating materials, offering thermal, soundproofing, and potential biodegradability benefits [62].

Another area where polyester composites find application is the packaging industry. Due to their chemical properties, these composites are ideal for producing various types of packaging. PET and rPET bottles and containers feature high mechanical strength and resistance to various chemicals. PET bottles can withstand pressures of up to 20 bars, making them ideal for carbonated beverages. PET and rPET composites are also used to produce films and packaging trays. PET films have excellent barrier properties, protecting products from moisture and oxygen. The thickness of PET films typically ranges from 12 to 50 μm, providing adequate protection for food products.

PET and rPET composites are also used in the electronics industry to produce various components due to their insulation and mechanical properties. PET and rPET are used for electronic device casings, such as computers, televisions, and mobile phones. These casings feature high-impact resistance and excellent electrical insulation. The impact resistance of PET casings is approximately 20 kJ/m². PET composites are also used to produce insulating elements in electronic devices, such as insulation tapes and thermal pads. PET's thermal conductivity coefficient is approximately 0.3 W/(m·K), making it an effective thermal insulator [63].

The textile industry also benefits from the properties of PET and rPET composites, which are used to produce various textile products. PET fibers are utilized in the production of clothing fabrics and technical textiles. These fibers exhibit high tensile strength and resistance to atmospheric factors. The tensile strength of PET fibers is approximately 450 MPa, making them ideal for producing sportswear and industrial garments [64].

rPET composites are also used to produce filaments for 3D printers, which have gained significant popularity in recent years. These filaments exhibit good adhesion to the substrate and thermal stability, enabling high-quality prints. The melting temperature of rPET filaments ranges from 220 to 250°C. Compared to filaments made from polylactic acid (PLA) or acrylonitrile-butadiene-styrene (ABS), PET for 3D printing can be entirely recycled. A notable feature of this filament is its transparency and ease of coloring, enhancing the visual properties of the final print. Additionally, unlike ABS, it does not emit toxic fumes during printing, significantly improving user safety. However, using PET in 3D printing involves certain challenges, such as the need for precise filament drying before printing to prevent brittleness caused by hydrolytic degradation. Proper printing speed and even temperature distribution are also crucial to achieving a high-quality final product [65].

PET/RPET COMPOSITES AND GREEN CHEMISTRY

With growing ecological awareness, increasing attention is being devoted to materials and technologies that can contribute to environmental protection. Although rPET is perceived as a step toward sustainable development, significant challenges related to its production and disposal conflict with the principles of green chemistry. This subsection analyzes PET/rPET composites in the context of green chemistry, assessing their environmen-

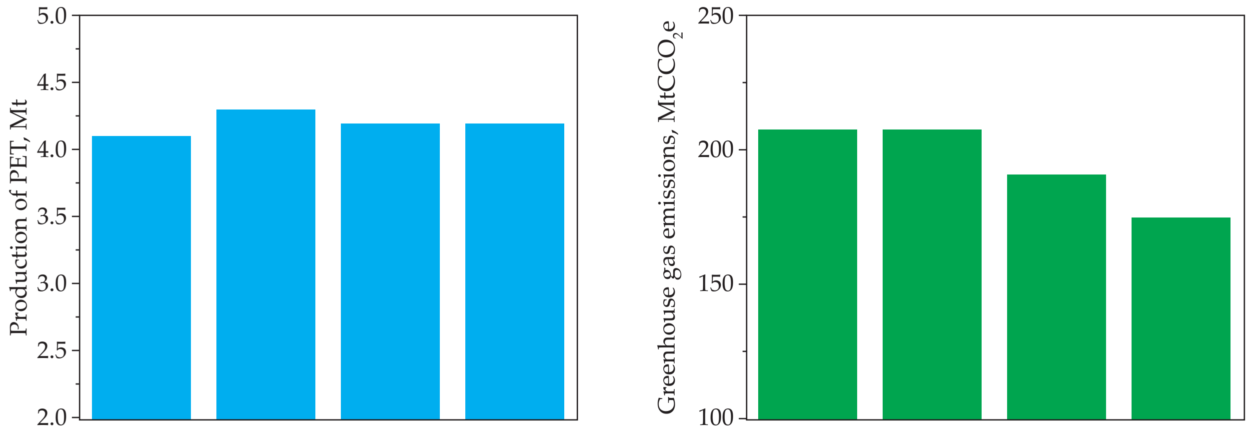

Fig. 6. Correlation between greenhouse gas emissions and PET production

tal impact and comparing them with more eco-friendly alternatives.

Environmental impact of PET/rPET composites

Greenhouse gas emissions

The production of PET composites is associated with high greenhouse gas emissions, which constitute one of the primary environmental concerns related to this material. Producing PET from fossil-based raw materials generates approximately 2.17 $MTCO_2E$/Short Ton. This process includes the extraction of crude oil, its processing, and polymerization, all of which contribute to a significant carbon footprint. However, recent years have shown a downward trend in greenhouse gas emissions during polymer production, including PET (Fig. 6) [66–68]. One reason for this reduction is the increasing use of rPET as a supplement. Recycling PET into rPET reduces CO_2 emissions but does not eliminate them. rPET production generates approximately 1.04 $MTCO_2E$/Short Ton. This reduction is achieved by avoiding the extraction and production processes required for virgin PET. However, the recycling process, including sorting, cleaning, and reprocessing used plastic, also demands considerable energy. While rPET is more environmentally friendly than virgin PET, its production still results in significant greenhouse gas emissions, undermining its neutrality compared to materials aligned with green chemistry principles [69]. An alternative approach could involve designing PET products with longer life spans, indirectly reducing waste generation.

Energy consumption

The production of PET and rPET composites is energy intensive. Producing 1 kg of virgin PET requires approximately 71.2 MJ of energy, encompassing processes such as crude oil distillation, chemical synthesis, and polymer formation (CPME). Comparing these values to materials compatible with green chemistry principles reveals stark differences. Biopolymers like PLA require significantly less energy during production, with 1 kg of PLA demanding approximately 62.5 MJ. This makes PLA production far more sustainable [70]. Producing biopolymers from renewable resources, such as corn starch, not only reduces energy consumption but also decreases dependence on fossil fuels [71].

Microplastic pollution

One of the most critical issues associated with PET/rPET composites is microplastic pollution. Microplastics are small plastic particles ranging from 1 nm to 5 mm, which result from the degradation of larger plastic fragments. Microplastics have been detected in every ecosystem on Earth, including human and animal tissues. They are challenging to detect and remove, and their presence in the environment has severe consequences for ecosystems and human health. High concentrations of microplastics in the human body may cause inflammation, reduced immunity, and increased risks of neurodegenerative diseases or cancers [72]. It is estimated that around 8 million tons of plastic enter the oceans annually, a significant portion of which consists of microplastics. These particles are ingested by marine organisms, leading to the accumulation of plastic in the food chain, affecting human health through the consumption of fish and seafood. It is estimated that humans consume between 39 000 and 52 000 microplastic particles annually [73]. Studies on rodents have shown that microplastics accumulate in organs such as the brain, lungs, spleen, kidneys, and reproductive system [74–76].

Depolymerization of PET composites

Deep eutectic solvents (DES) are becoming increasingly popular in depolymerizing PET due to their ecological nature, high efficiency, and adaptability to various reaction conditions. DES consist of a hydrogen donor and acceptor, forming a low-melting system. As a result, they can dissolve PET by weakening ester bonds, and facilitate glycolysis, hydrolysis, or alcoholysis reactions to obtain monomers [77–79].

DES are used in various PET depolymerization methods, such as: glycolysis – using ethanediol (EG) and DES as a catalyst leads to bis(hydroxyethylterephthalate) (BHET); hydrolysis – DES in the presence of water and catalysts can accelerate the decomposition of PET to terephthalic acid (TPA); alcoholysis – e.g. using methanol or ethanol to obtain dimethyl terephthalate (DMT) [80–82].

Deep eutectic solvents are a promising alternative to traditional PET depolymerization methods, allowing for more ecological and economic recovery of monomers. Further research on their application may contribute to more sustainable recycling of plastics. DES are gaining importance as ecological and effective agents in the depolymerization processes of polyethylene terephthalate (PET) due to their unique features, such as non-toxicity and biodegradability, ability to be modified, high efficiency at lower temperatures than traditional catalysts, and lower costs of their synthesis. However, to fully benefit from the potential of DES for PET depolymerization, several limitations must be overcome, such as the need to separate monomers from DES residues, optimization of reaction conditions and an individual approach to the selection of the DES system for a specific process [79, 83, 84].

PET/rPET composites and the principles of green chemistry

Green chemistry aims to minimize the negative impact of chemical products and processes on the environment and human health. There are 12 principles of green chem-

Principles of green chemistry

- Prevent waste creation
- Maximize atom economy
- Design less hazardous chemical syntheses
- Use safer solvents and auxiliaries
- Design energy-efficient processes
- Use renewable feedstocks
- Avoid unnecessary derivatization
- Increase catalytic efficiency
- Design products to degrade after use
- Monitor processes in real time
- Minimize accident risks

Fig. 7. Principles of green chemistry

istry, developed by Paul Anastas and John Warner in the 1990s (Fig. 7).

Waste minimization

Green chemistry emphasizes minimizing waste at every stage of a product's lifecycle. While recycling PET into rPET reduces the amount of plastic waste sent to landfills, the recycling process itself generates waste that can be challenging to manage. Additionally, not all PET waste is recyclable due to contamination or excessive degradation, limiting the efficiency of the process. Physical degradation factors include UV radiation, temperature, and humidity. Chemical degradation can occur through hydrolysis, oxidation, or contact with other chemical compounds. Recycling PET packaging materials involves sorting (separating different types of plastics, such as PP and PVC) and treating them with sodium hydroxide solutions. The purpose of this NaOH bath is to remove mineral contaminants and adhesives from labels. However, this process can lead to significant hydrolysis of PET chains. Short PET chains terminated with hydroxyl groups are more prone to degradation at elevated processing temperatures than their untreated counterparts. Alternative materials aligned with green chemistry principles are designed to minimize waste during production. For example, biopolymers are biodegradable and compostable after use, eliminating the problem of long-lasting plastic waste.

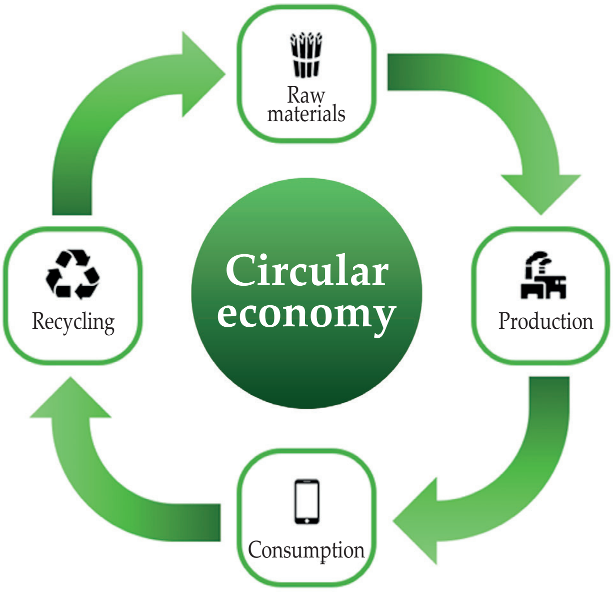

Fig. 8. Circular economy

Use of renewable resources

One of the key tenets of green chemistry is utilizing renewable resources. PET production primarily relies on oil refining processes, contradicting the concept of sustainable development. While using rPET addresses plastic waste, it does not resolve dependence on fossil fuels since virgin PET production continues to rely on these resources. Employing biopolymers and other materials derived from renewable resources is crucial for sustainable development. For instance, PLA is produced from corn, meaning its production is not reliant on petroleum. Such materials can be produced more ecologically, reducing environmental impact and supporting a circular economy (Fig. 8). Bio-PET, produced from sugarcane, offers a promising solution. It shares the same thermal and mechanical properties as petroleum-based PET. However, the higher cost of bio-PET, stemming from the cultivation and processing of raw materials, remains a drawback [85].

Designing environmentally friendly products

Green chemistry promotes designing products that are environmentally friendly during both production and use. PET/rPET composites, despite their advantages, such as strength and versatility, are challenging to recycle completely, and their long lifespan in the environment poses ecological issues. Designing products in line with green chemistry involves creating materials that are easily recyclable, biodegradable, or reusable in other industrial processes. While PET can be recycled multiple times, it is not biodegradable. This means that once PET loses its recyclability, it will require costly storage or disposal. Laboratory work aimed at making PET biodegradable offers a promising solution. For instance, the PETase enzyme, a type of esterase, can break down PET through hydrolysis, yielding mono-2-hydroxyethyl terephthalate (MHET). Studies have shown that this enzyme can degrade PET in just a few days [86].

Reducing toxicity

The production of PET involves toxic catalysts, such as antimony. Alternatives include less toxic compounds, like titanium-based catalysts. A greater challenge lies in toxic substances generated during chemical synthesis, such as unreacted, contaminated terephthalic acid. Green chemistry seeks to minimize toxicity in industrial processes, placing PET/rPET composites at a disadvantage compared to more eco-friendly alternatives.

CONCLUSIONS AND FUTURE PERSPECTIVES

Despite their numerous advantages, such as strength and recyclability, PET/rPET composites pose significant environmental challenges. Greenhouse gas emissions, high energy consumption, microplastic pollution, and long degradation times are the primary issues associated with these materials. In the context of green chemistry, which promotes waste minimization, renewable resource use, environmentally friendly product design, and toxicity reduction, PET/rPET composites are less favorable compared to more sustainable alternatives.

Using PET/rPET composites (especially those reinforced and modified with additives) for producing long-life products appears to be a reasonable approach, in contrast to single-use plastic products. Due to their high mechanical strength, durability, and special features (e.g., flame retardancy, antistatic properties, luminescence), these composites could be used for manufacturing products applied in various engineering fields, including civil engineering.

As part of the project LIDER14/0270/2023 titled "Non-conductive composite chain with an anchoring system" conducted at the Faculty of Civil Engineering, Cracow University of Technology, materials are being developed for manufacturing products such as non-conductive chains and anchors with special properties to enhance safety.

Authors contribution

K.A.O. – conceptualization, methodology, writing, project management, formal evaluation, funding acquisition; M.S. – writing, visualization, editing; P.R. – writing, methodology; T.M.M. – writing, methodology; R.P. – writing, visualization; Z.Z. – writing, visualization; K.F. – writing; D.B. – writing, review, and editing.

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Conflict of interest

The authors declare no known financial or personal competing interests that could have influenced the matters discussed in this article.

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