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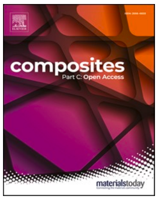

Plastics in the context of the circular economy and sustainable plastics recycling: Comprehensive review on research development, standardization and market

Madina Shamsuyeva [*], Hans-Josef Endres

IKK - Institute of Plastics and Circular Economy, Wilhelm Gottfried Leibniz University Hannover, Address: An der Universität 2, 30823 Garbsen

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ABSTRACT

The purpose of this study is to review existing recycling technologies, standards and market situation for plastics recycling. The principal results show that mechanical recycling is the most well-developed recycling approach in terms of industrial feasibility . This approach enables development of plastic recyclates of various quality levels . At the same time, transfer of many research findings into practice is hindered due to the global plastic material flow, strongly differing regional waste management systems and lack of international recycling standards. This review shows that the development of a Circular Economy Model for plastics products requires close cooperation of scientists with standardization committees and industry.

1. Introduction

The industrial production of plastics started predominantly in the second half of the 19th century and showed dynamic growth regarding plastic types and volume [1,2]. Furthermore, the processing and performance properties of the plastics, like rheological, mechanical, thermal, structural, morphologic, and optical properties were highly improved. This improvement was achieved using various plastic additives such as stabilizers, colorants, plasticizers, fillers and reinforcing fibers, ultraviolet absorbers, antioxidants as well as processing aids including lubricants and flow promoters. [2] Parallel to the progress in plastics chemistry, plant manufacturers took part in this expanding market and developed corresponding processing technologies, like extrusion and injection moulding [3]. Simultaneous development of the plastics chemistry and the processing plants contributed greatly to the technical evolution in the fields like medicine, transport, electric and electronics, building and construction. Furthermore, this development enabled cost reduction of the products and services offered by these fields and made them accessible to a broader range of society.

At the same time, until the last decades the development of plastics industry represented a so-called “Linear Economy Model” focused on the useful life of plastic products. This model is based on a principle “take, make and dispose” [4]. Linear Economy Model is predominantly centered on two assumptions: firstly, the availability of fossil resources is endless and, secondly, the recovery and reclaim of the plastic products after their useful phase is neither required nor desired. During this period, the focus of the plastics industry was to improve the production efficiency, quality and design of the plastics products which best satisfy consumers’ preferences. The waste management was not a part of the Linear Economy Model. As a result, a great amount of plastic waste, which has not been disposed properly, landed in the environment [1,5]. Furthermore, complex design of plastic products leading to challenges in disassembly or dismantling promoted losses from the recycling loops. Both plastics as well as the released plastic additives lead to environmental danger for living organisms [6,7]. In the recent years, the growing environmental awareness at social and legislative levels promoted introduction of the global Circular Economy Model (CEM) in the plastics industry. This model suggests effective and efficient recycling of the plastic waste generated after its useful life [4].

The aim of this article is to provide a review about the latest research development in the recycling of plastics waste, existing recycling standards and current market situation.

Currently, introduction of the global CEM faces numerous challenges associated with differences in waste management systems, regional economic situations and strategies, as well as the legal and social attitude [8–10]. Consequently, various mandatory legal approaches and advisory guidelines promoting higher recycling rates and/or reduction of demand on primary (or virgin) plastics are implemented at a state,

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[*] Corresponding author.
E-mail address: shamsuyeva@ikk.uni-hannover.de (M. Shamsuyeva).

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national or international level in many regions like USA, Japan, China or European Union (EU). These approaches can be classified as setting targets for mandatory recycling rate, targets for minimum recycled content, use of recycling labels and / or various re-use and deposit systems for plastic products:

a *Mandatory recycling targets indicatet a certain percentage of a material, which must be diverted from the waste stream and recycled in a certain period of time.*

For example, in 2018 plastics packaging recycling rate in EU, Switzerland and Norway was 41% [11]. In the same year, European Union set recycling target for all packaging as 65% by 2025, 70% by 2030 and for plastics as 50% by 2025 and 55% by 2030, respectively [12]. This means that by 2025, 10 million tons of plastic recyclates will be used in European plastics industry [11].

b *Mandatory targets for minimum recycled content*

In California, starting from 2022 all plastic bottles covered by the state's container redemption program are required to average at least 15% of post-consumer recycled resin [13].

c *Recycling labels*

The **Fig. 1** represents selected recycling labels used worldwide for the packaging made of various materials. The Mobius loop composing of three arrows is the most commonly used recycling symbol in the world. This label was originally designed by Gary Anderson in 1970 as a part of a contest for the Container Corporation of America (CCA) for the description of paper recyclability. After the CCA dropped the trademark application, the symbol became a part of the public domain. [14] Currently, there are numerous variations of this label and their use is not regulated. Furthermore, the Mobius loop does not always indicate that the material is based on a recyclate or is recyclable, although in some countries there are local laws or standards restricting its use [15–17]. Besides the three-arrow symbol there are further recycling labels used by the packaging industry such as “Green Dot” or “Triman”. At the same time, there are numerous organizations worldwide, which provide certified labels indicating exact content of recycled plastics in a given material or product like “RAL Gütezeichen” (RAL quality mark) or “flustix”.

These recycling labels are to distinguish from the resin identification codes (RIC) showed in **Fig. 2**. RICs represent a number in a solid equilateral triangle and are used for the identification of resins, but not as a recycling code [18]. The RIC was established in late 1980s based on a Mobius loop, in order to facilitate recycling of post-consumer plastic waste. In 2013 the RIC symbols were updated to a solid equilateral triangle to eliminate the consumer confusion about recyclability. However, the former version is still commonly used in the industry.

Nowadays, the RIC numbers higher than 7 are defined regionally and not harmonized internationally. For example, in 1997 the European Commission established an identification system for packaging materials which goes up to 99 and contains plastics, paper and fibreboard, metal, wood, textiles, glass and various composites [19]. In China, the RIC system includes 140 numbers specifying different plastic resins [20]. As a result, depending on the region, the same RIC may refer to a different substance. For example, according to the Chinese system the number 20 refers to the cellulose nitrate and according to the EU system to the corrugated fibreboard.

Recycling label is a powerful tool in term of public relations and customer acceptance. However, nowadays there is a broad range of recycling labels. As a result, the diversity and complexity, especially if several symbols are used simultaneously, leads to confusion by consumers [16]. Furthermore, there is no analytical method enabling differentiation between recycled and primary polymers. As a result, the information about the recycled content in a given product cannot be verified. Consequently, use of the certified recycling labels is very important, in order to ensure transparency along the entire supply chain.

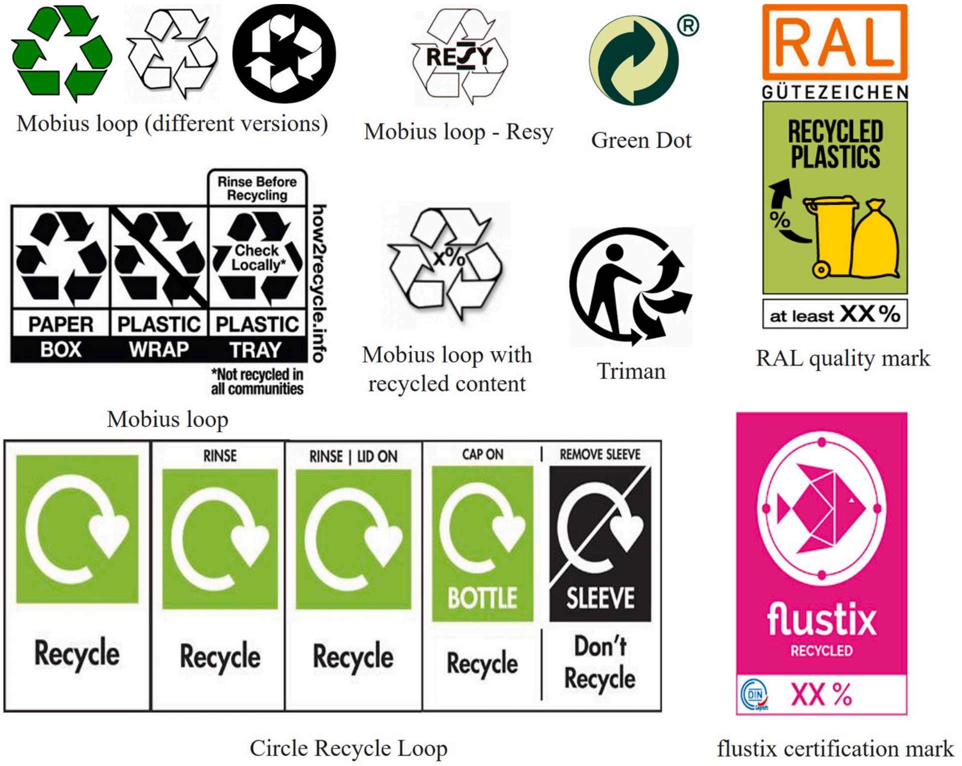

Fig. 1. Selected recycling labels for various packaging used worldwide.

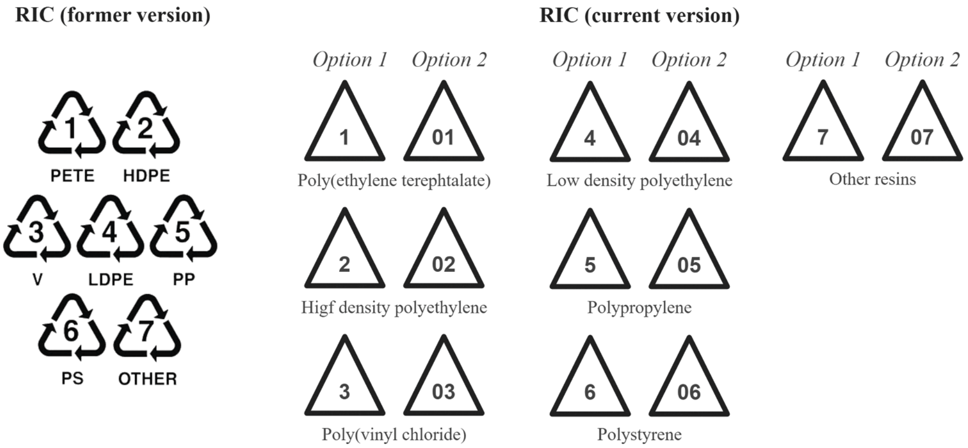

Fig. 2. Resin identification codes (RIC) according to ASTM D7611.

d *Support of various types of re-use and deposit models for plastic products*

Besides recycling of the already generated plastic waste, there are numerous business models promoting less use of plastics packaging. One example among such models is a deposit-refund system with a surcharge on an item during purchase and a refund by return of the plastic packaging. Further models represent “refill on the go” implying use of in-store dispensing systems, “return from home”, where the packaging is collected by a service from home, . “return on the go” represents use of a deposit return machine or “refill at home” assumes refill delivered through a subscription service. “B2B” includes companies reusing their own transport packaging. [21] Practicability of these methods strongly depends on an application field and a local social attitude.

In order to enable sustainable integration of the CEM, establishment of effective and efficient recycling approaches as well as the development of a global supply chain for recycled plastics should be the main focus of the plastics industry.

2. Recycling of plastics – recycling processes

There are two principal recycling approaches: “closed-loop recycling” and “open-loop recycling”. [22–25] In the case of the “closed-loop recycling” the inherent properties of a recycled plastic are not significantly changed and the recyclate can be used in the same application as the primary material, for example bottle-to-bottle recycling [26]. As an alternative, “open-loop recycling” means that the inherent properties of the recycled plastic are changed and the recyclate cannot be used for the same application again. At the same time, it can be used for manufacture of plastic products for other applications, for example bottle-to-fiber recycling [27]. The appropriateness of each approach is considered individually, since it dependents on various properties like contamination grade of a given plastic waste, polymer properties as well as the application-specific approval requirements. The main recycling technologies for the recovery of a plastic material, chemical raw materials, biomass and gasses or energy from plastics waste can be summarized as follows [23,28,29]:

1. Mechanical recycling: processing of plastic waste into secondary raw material without significantly changing the chemical structure of a given polymer.
2. Chemical or feedstock recycling: depolymerization of a given polymer and recycling of the resulting chemical constituents.
3. Physical recycling: solvent-based recycling enabling recovery of a plastic material without changing the chemical structure of a given polymer.
4. Biological or organic recycling: aerobic or anaerobic treatment of biodegradable plastic waste under controlled conditions using microorganisms resulting in stabilized organic residues and various gasses.
5. Energy recovery: production of useful energy using direct and controlled combustion of plastic waste.

These approaches are going to be reviewed in the following sections.

2.1. *Mechanical recycling*

Mechanical recycling represents a partially variable combination of principal processing steps like collection, identification, sorting, grinding, washing, agglomerating and compounding [28], **Fig. 3**. The major advantage of the mechanical recycling is that this approach is suitable for a decentralized implementation. The mechanical recycling plants are simple and inexpensive, have a relatively low demand on energy and resources compared with plants required for chemical or physical recycling. Currently, optimization of the above-mentioned processing steps enables partial improvement of the output material (plastic recyclate) properties like smell, purity, color, etc. However, in general the quality of the plastic recyclates is strongly dependent on the quality and purity of the input-stream (plastic waste).

The term “plastic recyclate” is used for description of different forms of recycled plastic materials. At the same time, this term is not legally protected and is defined differently depending on the source [28,30,31]. Most commonly used plastic recyclate forms are:

- “regrind” (or flakes) representing a product resulting from shredding or grinding
- “regranulate” representing a plastic recyclate manufactured using extrusion without changing the chemical composition of the input stream
- “recompound or regenerate” representing a plastic recyclate with a modified chemical composition compared to the input stream

2.1.1. *Regrind*

The recyclates in the form of a regrind are commonly used a in building and construction applications as a filler and partial substitute for sand aggregates [32–35]. Both plastics as well as the fiber-reinforced polymer composite regrinds are used for self-compacting concrete [34–36] and mortar [32,33], **Fig. 3**. This approach shows promising potential for lightweight constructions. Particularly, the use of recycled high impact polystyrene (rHIPS) and low-density polyethylene (rLDPE) as a substitution for the sand in the concrete, shows decrease of workability, density and compressive strength with increase of the recycled plastics amount [34]. Especially, the density reduction indicates

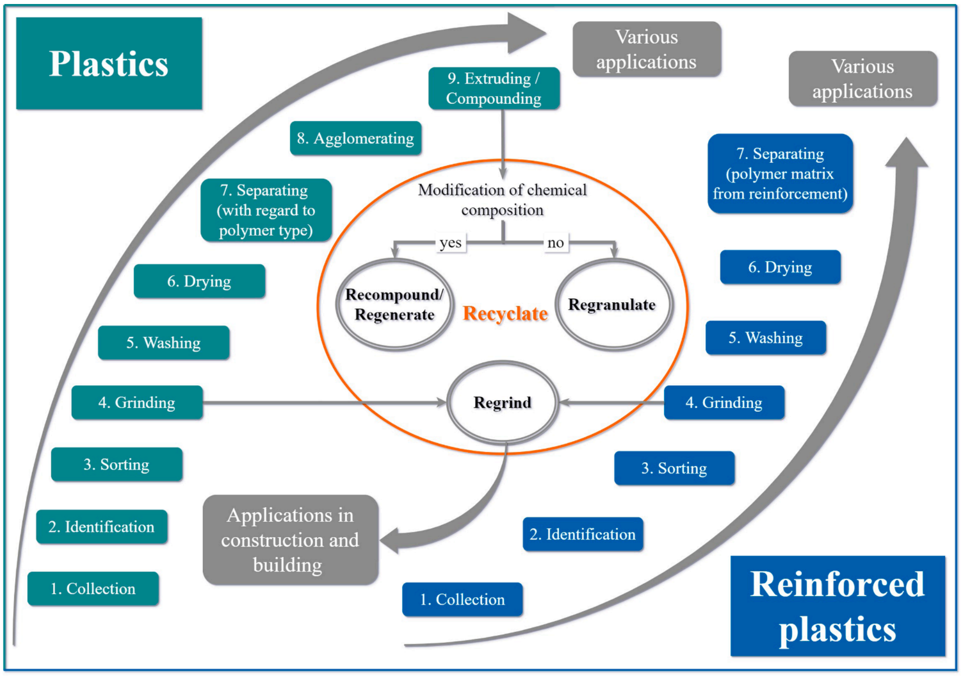

Fig. 3. Principal steps of the mechanical recycling.

promising potential of this material for lightweight structural concrete. This performance is associated with the difference between the density of sand (1631 g/cm^3), HIPS (1,08 g/cm^3) and LDPE (0,91 – 0,94 g/cm^3). At the same time, the morphology of the regrinds affects certain properties of the resulting materials. For example, the grain size of a recycled high-density polyethylene (rHDPE) and a recycled poly (ethylene terephthalate) (rPET) used as fillers for unfired clay bricks influences thermal properties. Particularly, due to the higher porosity resulting from the use of larger grain-sized regrinds the thermal conductivity and specific heat capacity properties can be improved by 40% and 55%, respectively [37].

2.1.2. *Regranulate and regenerate*

Recyclates in the form of regranulates and regenerates (or recompounds) are predominantly used in the production of plastic products using extrusion and injection moulding. This approach enables manufacture of various plastic compounds including both mixtures of different plastics (polymer blends) or use of fillers/fibers (polymer composites). Table 1 represents a summary of reported plastic and composites made of recycled plastics. Polymer composites represent a very large and diverse category of materials for lightweight applications [38–45,55]. Main application fields of the composites are aircraft, automotive, building and construction, sport and leisure industries [38,45–54,56,57]. Various recycling approaches of polymer composites are described in the literature [58–68,112,161].

Plastic blends: Blends can be manufactured, for example, by mixing recycled plastic of one type with a virgin or recycled plastic of another type or recycling of a plastic product already composing of different plastic types. Plastic products such as multilayered packaging films often consist of different polymer layers. Due to the very low thickness of the individual layers, it is not possible to separate these materials. Consequently, understanding of the processing behavior of such multilayer mixtures plays an important role in the context of CEM. It has been shown that the rHDPE/rPET composites show typical thermal degradation process as a virgin blend [81]. At the same time, selection of a suitable processing temperature plays significant role on the mechanical performance of the resulting composite. The impact strength, flexural strength and modulus, tensile strength and modulus of rHDPE/rPET (75 / 25 w/w) composites injection molded at 185 °C are about 81%, 16%, 24%, 39%, and 18% higher than those of the composites injection molded at 270 °C. [82]. The temperature of 185 °C is lower than the melting temperature (T$_m$) of PET, but higher than the T$_m$ of PE, while 270 °C is above the T$_m$ of PE and PET. According to the authors, these results are associated with the morphology difference of the rPET phase in the composite. Particularly, the rPET microfibers are melted during the processing at 270 °C and deformed into spherical particles and irregular blocks, while processing at lower temperature preserve the fiber structure and the corresponding reinforcing effect.

Table 1
Overview of the reported materials made of recycled plastics.

Material Composites and blends	Reference
PET/PETG	[69]
Disposable chopsticks/PLA	[54]
Bagasse or pine /rHDPE	[70]
Piassava/rHDPE	[71]
Flax/rHDPE	[72]
Sisal/rHDPE	[73]
Hemp/rHDPE	[74]
Flax/PLLA	[75]
Kenaf / rPET and rPP	[76]
Kenaf / rPE and rPP	[77]
Sisal / PLA	[78]
Husk fiber-reinforced rLDPE	[79]
Coriander straw / rPP and bio-rLPDE	[80]
rHDPE/rPET	[81,82]
Wood-plastic-composites	
rABS	[83]
rHPDE	[85–87]
rLDPE	[88]
rPP	[89]
rABS	[83]
rPE and rPP	[90,91]

Polymer composites: Mechanical performance of a composite is mainly dependent on the used reinforcement. As a result, reinforcement of a recycled and a virgin plastic of the same type of reinforcement can result in composites with similar mechanical performance. For example, the virgin ABS and rABS possess elongation-at-break values of 52% and

3%, respectively. However, introduction of 50 wt.% wood fibers results in composites with impact strength of 63 J/m (ABS) and 55 J/m (rABS) and elongation-at-break ranging from 1,05% to 1,4% for ABS and 0,8% to 1,02% for rABS. [83]. Further example represents short PET fiber-reinforced recycled poly (ethylene glycol-co-1, 4-cyclohexanedimethanol terephthalate) (PETG). PETG is a material applied in packaging industry. The composite containing 30 wt.% of PET fibers results in a notched impact strength of approx. 12,8 kJ/m^2 corresponding to that of a GF-reinforced virgin PP containing the same proportion of fibers [69]. Similar results are observed in the case of tensile properties of polylactic acid (PLA) reinforced with recycled disposable chopsticks. Chopsticks is one of the major waste source in countries like Taiwan, China and Japan [54]. Depending on the reinforcement content, these composites resulted in tensile properties three times higher compared with that of a neat PLA.

Combination of recycled polymer matrix with natural fibers is especially advantageous from the ecological point of view. Examples of commonly used recycled thermoplastics are rHDPE, rPET or polypropylene (rPP). The resulting composites are rHDPE reinforced with bagasse or pine [70], piassava (*a palm tree*) [71], flax [72], sisal [73] or hemp fibers [74], flax fiber-reinforced PLLA [75], kenaf fiber-reinforced rPET/rPP [76] or rPE/rPP [77], sisal fiber-reinforced PLA [78] or corn husk fiber-reinforced rLDPE [79]. Similarly, use of exotic fibers like coriander straw [84] for the manufacture of composites with rPP and bio-rLPDE gained research interest [80]. Furthermore, wood-plastic-composites (WPC) represent one of the most commonly investigated composites with regard to the use of various recycled thermoplastics, like rHPDE [85–87], rLDPE [88], rPP [89], rABS [83], blend of rPE and rPP [90,91].

2.1.3. *Multiple recycling*

Ideally, the closed-loop recycling implies that a plastic material does not change its inherent properties not only after the first recycling loop, but also after multiple recycling loops. However, in the case of the mechanical recycling, implementation of multiple recycling loops without change of the plastics' properties is possible only for few times. This limitation is associated with the deterioration of the molecular structure of the polymers caused by shear during extrusion processing at a high temperature and under a high pressure. The umbrella term for the reduction of material quality after recycling is known as "downcycling" [92]. However, it is important to consider that this term is not protected. Consequenlty, depending on the application field it can also be used for the description of deterioration of various processing and performance properties preventing closed-loop recycling such as degradation of rheological or mechanical properties..

In general, the multiple recycling of plastics and plastic composites shows that there is a certain material-specific number of recycling loops, over which selected mechanical properties of the material can be maintained. Furthermore, the change in the degree of crystallinity associated with multiple recycling affects mechanical properties like hardness, flexural fatigue resistance or flex life, softening temperature, elongation-at-break and sometimes impact strength [93]. As an example, continuous degradation during processing of PP in a melt state gives rise to decrease in molecular weight and a simultaneous narrowing of the molecular weight distribution [94]. Additionally, if PP is processed using extrusion at high temperatures and shear, the presence of oxygen and impurities, like hydroperoxide and catalyst residues, promote further degradation. The PP chain scissions lead to a decrease of viscosity and a considerable loss in mechanical properties, making the material more fragile and yellowish [95]. Multiple recycling of PP [94] and increase of its processing temperature result in a higher crystallinity, which is attributed to the crystal growth using molecule segments released by the scission of macromolecules caused by thermal and thermo-oxidative and/or mechanical degradation. This behavior is mainly reflected in destructive mechanical properties such as decrease of break stress or break energy. On the other hand, strain properties like modulus are only slightly affected. The maximum number of recycling loops is individual for every plastic or composite type. For instance, in the case of composites made of flax and poly-L-lactide (PLLA) with varied fiber content, the tensile properties are conserved until the third cycle of injection moulding [75]. Further recycling loops result in a considerable decrease of mechanical performance caused by the lowering of the molecular weight, decrease of glass transition temperature and shortening of the fiber length as well as a separation of fiber bundles. Similarly, multiple recycling of biocomposites made of surface-treated sisal fiber-reinforced PLA [78] shows that the tensile properties decrease with every further recycling loop, especially after the third loop. At the same time, the impact properties decrease after the first recycle, whereas flexural properties show fast decrease rate only after the fourth recycle. Beside the above-mentioned changes in the polymer bulk, the surface roughness of the composite increases after each recycling loop, especially after the fourth recycle, which is attributed to the hydrolytic degradation of PLA. Consequently, both flax/PLLA and sisal-reinforced PLA should not be recycled beyond the third recycling loop. Multiple recycling with five loops of coriander straw fiber/PP and bio-LPDE [80] results in only slight loss of flexural and tensile properties by about 10% compared to the specimens made of virgin plastic, whereas the impact strength is considerably increased. This increase of the impact strength, which is observed also after the first recycling is attributed to the reduction of the fiber length, making the material more ductile [96]. Similarly, mechanical properties of the recycled composite made of PP reinforced with thermotropic liquid crystalline polymer (TLCP) are conserved after three recycling loops [97]. This is achieved due to the thermoplastic nature of TLCP. Namely, the in-situ TLCP/PP blend is capable of generating TLCP fibrils, since dispersed TLCP droplets are elongated into oriented fibrils during polymer processing, especially in the case of elongation flow [98,99]. On the contrary, the shortening of the GF caused by multiple recycling leads to a considerable deterioration of the tensile properties [97].

To sum up, it is obvious that the different types of plastics and fiber-reinforced polymer composites show different behavior regarding multiple recycling potential. However, there is still lack of systematic information on the effect of molecular weight distribution and crystallinity change of different plastic types, fiber shortening and morphology changes in the case of different composites like cellulose-based, thermoplastic, and high-performance synthetic fiber-reinforced polymer composites. Consequently, it is impossible to derive an accurate general statement regarding the influence of a multiple recycling on material-specific properties of the recyclates and practical applicability of the multiple recycling in the context of CEM without modification of the recyclates using additives.

2.1.4. *Improvement of recyclate properties using additives*

Optimization of individual recycling steps as well as the purification of the melt during extrusion by means of filter systems or use of various additives is used to reduce downcycling. **Table 2** represents additives and further approaches used for the improvement of recycled plastics performance. For example, in order to lengthen the polymer chain, reactive copolymers of styrene, glycidyl methacrylate, and butyl acrylate are used during extrusion of rPET [100]. This approach results in the increase of tensile strength from 32 MPa to 58 MPa [100]. Furthermore, maleic anhydride (MA)-grafted copolymers are the most commonly used compatilizers in the case of recycled thermoplastics such as rPP and rPET [101] or composites like pine wood waste/rLDPE [88], sawdust of softwood radiata pine/rHDPE [85] or wood fluor/rPE [86], rGF/PP [102], rice husk/organoclay/rHDPE/rPET [81], coriander straw fiber/rPP and recycled bio-LPDE [80] or wood sawdust and post-consumer polyolefin mixture [90,103].

The use of compatibilizing agents based on polyethylene-grafted maleic anhydride and ethylene-glycidyl methacrylate is essential for the improvement of tensile properties of rHDPE/rPET filled with organoclay and rice husk [81]. In the case of composites made from

Table 2
Summary of the studies on use of compatibilizers and fiber surface treatment methods for development of materials made of recycled thermoplastics.

Material	Compatibilizer and surface treatment for fiber-matrix-adhesion	Reference
rPET	Reactive copolymers of styrene, glycidyl methacrylate, and butyl acrylate	[100]
rPET	Maleic anhydride (MA)-grafted copolymers	[101]
Pine wood / rLDPE		[88]
Radiate pine/rHDPE		[85]
Wood fluor/rPE		[86]
Coriander straw fiber / rPP and recycled bio-LPDE		[80]
Wood sawdust / recycled polyolefin mixture		[90,103]
Rice husk/oganoclay /rHDPE and rPET	Polyethylene-grafted maleic anhydride and ethylene-glycidyl methacrylate	[81]
Wood flour / rPP	Starch gum	[89]
rPET/rHDPE	Ethylene glycidyl methacrylate copolymer	[82]
Hemp/rHPDE	Surface treatment using NaOH and MA	[74]
Sisal/rHDPE	Multistage surface treatment using NaOH, MA, and benzoyl peroxide	[73]

wood/rHDPE the use of maleic anhydride grafted PP (MAPP) or copolymers of PE and PE wax leads to comparable or even higher mechanical properties than that of the composites made of the virgin HDPE [85,86]. Besides MA-based copolymers the use of a starch gum as a coupling agent for wood flour / rPP composites [89] or the use of ethylene glycidyl methacrylate copolymer for rPET/rHDPE composite shows potential with regard to increase of the mechanical performance [82]. Besides modification of the plastic, surface treatment of fibers for the improvement of the compatibility is a promising solution. For example, combined surface treatment of hemp fibers using NaOH and MA [74] or multistage treatment using NaOH, MA, and benzoyl peroxide of sisal fibers [73] for the integration in rHDPE, which in both cases leads to improvement of flexural properties of the manufactured composites.

To sum up, the use of additives enables improvement of mechanical properties of recycled plastics. However, considering an industrial process this use of is associated with further expenses leading to a higher cost of the resulting plastic recyclates.

2.1.5. *Quality and marketability of the mechanically recycled plastics*

Currently, mechanically recycled plastics are the most commonly commercially available and used recyclates. At the same time, compared with virgin plastics industrial use of recyclates is disadvantageous with regard to application-specific requirements and cost. The highest application-specific quality requirements are associated with food-grade recyclates, for example in the case of bottle-to-bottle recycling of PET. Recycling technologies approved for the manufacture of recyclates suitable for food contact must be certified by the Food and Drug Administration (FDA) or European Food Safety Authority (EFSA) according to a special examination procedure called “challenge test” [104–106]. The challenge test demonstrates purification efficiency of a given recycling technology. The aim of the test is to reduce the amount of chemical contaminants to a concentration that does not pose risk for the human health. During the challenge test plastic materials are contaminated with a predefined mixture of hazardous chemicals (surrogate) under controlled conditions for a certain time. Afterwards, recycling technology is used to remove the surrogate from the contaminated plastic materials. Specially designed challenge tests are used for bottle-to-bottle recycling of PET or polyolefins [104,105]. In general, use of the mechanically recycled plastics in further applications with high approval requirements like medicine is currently not possible. These limitations are associated with the low traceability of the plastic waste, and lack of a commercially implementable high quality mechanical recycling technologies. As discussed above, improvement of the mechanically recycled plastics’ quality is possible to a certain extent. However, each additional processing step and use of additives is associated with increase of the production cost. The **Fig. 4** represents a simplified comparison of quality and cost of a mechanically recycled plastic and a virgin plastic including three main regions. First region contains recyclates of the lowest material quality, i.e. disposal of plastic waste is more important than the quality of the produced recyclates. These types of recyclates are associated with the waste disposal charge and sale of the recyclate, i.e. recycler is paid both for the disposal of plastic waste and for the sale of the manufactured recyclate. The manufactured recyclates can be used for inferior applications like a non-functional filler. The second region represents a price-performance area, where recyclates can compete with virgin plastics with regard to the material quality, but not cost. Two main factors limit the price competitiveness of the plastic recyclates: improvement of the recyclate quality is associated with additional processing steps and use of processing aids and low cost of the corresponding virgin plastics. As virgin plastics become more expensive, the price difference gets smaller. The third region represents high-quality plastics, which require special approval such as food-grade or surface optics. Manufacture of the high-quality recyclates is associated with multistage complex recycling processes. Currently, in this price-performance region mainly ecological and not economic criteria represent the driving force of the plastics recycling. Sustainable introduction of a “Design for Recycling” into plastics industry as well as a better pre-sorting of mixed waste streams would considerably simplify this challenge and reduce the processing cost of recyclates in the second and third regions. [29]

2.2. *Chemical recycling*

During chemical recycling the polymers iare depolymerized under controlled conditions and the recovered chemical constituents are used as a feedstock for production of new materials [28,30,107]. Chemical and feedstock recycling are used as synonyms [28,107]. In contrast to the mechanical recycling, the recyclate quality achieved at the end of the chemical recycling is comparable with the quality of virgin plastic materials. As a result, this approach enables use of the recycled materials in applications with high approval requirements like medicine. However, methods of chemical recycling are not yet established and the position within the circular economy has not yet been finally determined [108]. Chemical recycling is mainly used for recycling of post-consumer PET, PE and PP [109,110].

Chemical recycling is an umbrella term for several processes, which are classified into two main groups: thermolysis and solvolysis [107]. Thermolysis involves various decomposition reactions caused by different thermal treatment methods. These processes result in hydrocarbon mixtures of different compositions. After fractionation, the components of these mixtures can be used for example as a feedstock in the chemical industry [108]. Solvolysis includes chemically induced depolymerization reactions taking place in a solvent. The depolymerization products, monomers, can then be polymerized together with virgin raw components and further processed into plastics [29]. Due to the latter process step, chemically recycled materials cannot be traced directly. The recycling rate can be monitored only indirectly using a so-called “mass balance approach” [111]. According to this approach, the amount of the recycled chemical raw materials and the virgin chemical raw materials are allocated at the beginning of the polymerization process by a third-party audited methodology. The allocated average amount of the recycled feedstock is used for the determination of the recycled content in a given plastic material. In fact, the allocated average proportion of the recycled material does not necessarily mean that an individual product made of this plastic contains any recycled material.

Main disadvantages of chemical recycling are high energy input, complex recycling plants and the use of special solvents. Due to the complexity of the technology, chemical recycling processes are set up

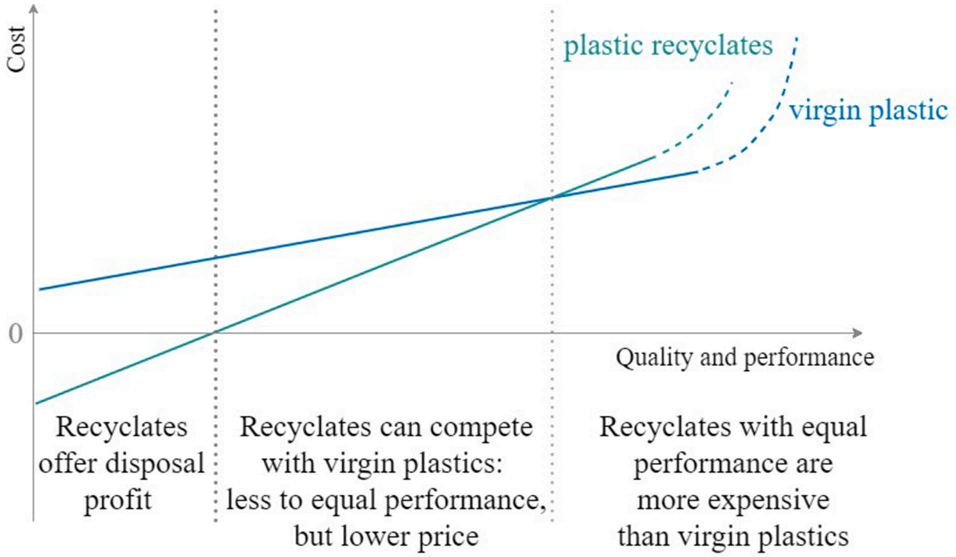

Fig. 4. Simplified comparison of assets and drawbacks of the virgin and recycled plastics manufactured via mechanical recycling.

centrally and carried out by chemical industry producing virgin plastics [108].

To sum up, nowadays mechanical and chemical recycling are the most commonly used and discussed recycling approaches. The main advantages and disadvantages of both approaches are summarized in **Table 3.** The appropriateness of the use of either of the methods or their combination should be identified depending on the application field of the resulting recovered material. Furthermore, it could be seen that despite of a dynamic development of both approaches, there is deficiency on data, especially, regarding multiple recycling and environmental assessment of both approaches.

Table 3
Advantages and disadvantages of chemical versus mechanical recycling. Based on previous publication [29]. Reproduced with permission from Röchling Stiftung GmbH.

Property	Mechanical Recycling	Chemical Recycling
Technical requirements for infrastructure / processes	Low	High
Possibility of decentralized processing	Possible	Currently technically challenging and uneconomic
Requirement on quality for input stream	High	Low - Medium
Quality of output material	Depends on the quality of input material. Moderate quality improvement using process parameters and additives is possible, but it is inversely proportional to the technical expense	Very high
Food regulatory approval of the output	In special cases possible	High
Possibility of multiple recycling	Limited	Possible
Industrial maturity	High	Depending on process, not fully mature
Cost	Low	High
Environmental assessment	Due to the lack of data on the entire lifetime including multiple recycling, quality improvement steps and application-specific use of the recovered materials an accurate comparison is currently not possible. Although regarding ecological effect, mechanical recycling is expected to be more advantageous.	

2.3. *Physical recycling*

Compared with the above mentioned approaches, solvent-based recovery of polymers without changing their chemical structure is a relatively new technology. Depending on the literature source, this approach is sometimes classified as a chemical [113], material [114] or plastic/polymer [115] recycling. During this process mechanically pre-treated plastic waste is dissolved in a suitable solvent and subjected to a number of purification steps. As a result, the desired polymers are separated from additives and undesired substances and recovered without changing the molecular structure. The output material represents a precipitated polymer, which can be re-used in a plastic processing. There are various patented physical recycling methods like CreaSolv® or Newcycling® or extended physico-chemical recycling methods like CreaSolv® - PolyStyreneLoop. The latter method includes thermal destruction of a hexabromocyclododecane [116]. Currently, physical recycling is used commercially for recycling of PP, PE or PS and various brominated flame-retarded plastics from waste electric and electronic equipment [114] or multilayered films composing of PE and PA or PE, PET and ethylene vinyl alcohol serving as an oxygen barrier [115]. The efficiency of the solvent-based processes depends strongly on the solubility of a given polymer in a certain solvent and interaction between solvent and polymer. Finally, physical recycling requires complex technical equipment.

2.4. *Biological recycling*

According to the international standard ISO 15270, aerobic or anaerobic treatment of biodegradable plastics waste using microorganisms, like bacteria or fungi, is called biological or organic recycling [28]. At the same time, biological recycling does not produce plastic material, which can be directly reprocessed. During this process, plastic waste degrades to stabilized organic residues, carbon dioxide and water in the presence of oxygen. In the absence of oxygen stabilized organic residues, methane, carbon dioxide and water are produced [117–120]. Enzymatic treatment represents one of the biological recycling sub-categories and is also-called as biorecycling [121]. In this case, the targeted degradation of a plastic component is realized using microorganisms. Nowadays, this approach is mainly used for recycling of PET [121,122] or blended textiles [123,124]. Enzymatic recycling enables recovery of polyester fibers from a mixed textile consisting of a polyester/wool [125] or polyester/cotton/wool [126] blends. The recovered polyester yarns can be afterwards used in the production of new garments or products [125]. Obviously, biodegradability of a given plastic is the main criterion for a successful implementation of this approach. Since most of the plastics are non-biodegradable, applicability of this method is very limited.

2.5. Energy recovery process

Energy recovery means heat, steam, or electricity generation using plastics waste as substitutes for primary fossil fuel resources. Although incineration is the most commonly used energy recovery method for plastic waste, further methods are described in the literature [133,134]. The direct combustion or co-combustion of plastic waste in municipal solid-waste incinerators operating according to the regulatory requirements for emissions and ash are used for energy recovery. [28] Similarly, as in the case of biodegradation, energy recovery from a plastic waste does not produce any plastic or polyme, which can be directly reprocessed as a recyclate . However, the recovered energy can be used for the manufacture of plastics. The most important parameter of the input stream is the calorific value [28]. Since most of the plastic waste is hydrocarbon in nature, it has a high calorific value.

In generall, this approach is preferred, especially in the case of heavily contaminated waste or a lack of waste treatment and sorting logistics. However, it is important to consider that after the combustion there is a certain amount of rest material. Particularly, the incineration bottom ash composition is usually within the following ranges: 5–15% ferrous metals, 1–5% non-ferrous metals, 10–30% glass and ceramics, 1–5% unburned organics, and 50–70% minerals [127]. As a result, the ash is used as a secondary source for ferrous and non-ferrous metals and glass [127]. Furthermore, during the last two decades large amount of the mineral portion was utilized in many European countries as a subbase layer in road constructions [128]. Similarly, the mineral portion is used in construction materials like mortar, concrete or pre-manufactured construction products like building blocks, lightweight aggregates or asphalt as a partial replacement for natural materials like sand or gravel [129,130]. The overall utilization rate of the ash in construction is around 54 wt.% [128].

In the past and in some countries even nowadays the incineration ash is landfilled or used for road construction on the landfill site. In certain regions the limit values defined for landfills for inert waste have been adopted for the utilization of the incineration bottom ash [128]. However, this type of landfilling represents a further possible waste source. Special risks are associated with the presence of high concentration on heavy metals like cadmium and lead in insufficiently sorted plastic waste [131]. Furthermore, there are 360 to 102 000 micro-plastic particles produced per metric ton waste after incineration [132]. As a result, landfilled incineration bottom ash represents a potential source for micro-plastic waste in the environment.

To sum up the main issues of this section, the mechanical, chemical and physical recycling approaches represent various material recovery processes. In contrast, biological recycling and energy recovery refer to biodegradation of the plastic waste and energy generation without direct material recovery. **Table 4** represents summary of the recycling approaches and the corresponding output materials. Except physical recycling all of the above-mentioned approaches are standardized at international level in ISO 15270 [28].

3. Standardization of plastic recyclates

Standardization plays central role in the sustainable introduction of CEM and establishment of a global supply chain for plastic recyclates. Due to the difference in economic, political and legal basis, currently, there are only few international standards in the field of plastic recycling. Presently, this supply chain is in its early development stage and there are mainly bilateral B2B cooperation models between recyclate suppliers and manufacturers of plastic products. The main prerequisites for the development of a functioning market for plastic recyclates are material quality, clear responsibilities for recyclate properties and supply guaranty. In order to meet these prerequisites, traceability of the recycled materials, standardized sampling and characterization methods for recyclates and products, which contain recycled content, must be ensured. At the same time, application- and product-specific requirements must be considered. Finally, complete and precisely defined material properties must be provided in technical and safety data sheets (TDS, SDS). The implementation of these requirements can be guaranteed by corresponding standards. which represent a valuable communication tool for supply chain. This section represents available recycling standards. Tables 5, 6 and 7 summarize the currently existing standards, technical specifications and reports at the international and European levels.

Table 4

Summary of commonly used plastic recycling processes and corresponding output materials.

Recycling approach		Process	Output
Biological / organic		Aerobic (composting) or anaerobic (digestion) treatment of biodegradable plastics waste under controlled conditions using micro-organisms (bacteria and fungi)	(i) in the presence of O_2: stabilized organic residues, CO_2 and H_2O(ii) in the absence of O_2: stabilized organic residues, CH_4, CO_2 and H_2O
		Specific decomposition of polymer using enzymes	Chemical raw materials
Energetic		Production of useful energy through direct and controlled combustion	Hot water, steam and/or electricity
Physical		Selective dissolution of plastics in a solvent without changing the polymer structure, e.g., CreaSolv® or Newcycling®	Recovered polymers of a selected type without changing the molecular structure
Mechanical		Mechanical processing of plastic waste into secondary raw material or products without significant change of the chemical structure of the plastic	Plastic recyclate: (i) regrind, (ii) regranulate and (iii) recompound/ regenerate
Chemical or feedstock	Thermolysis	Pyrolysis	Carbonized char, syngas and liquid hydrocarbon oils (pyrolysis oil)
		Gasification	High calorific value syngas (CO & H_2) and char (can either be combusted directly or used to synthesize products such asmethanol or ammonia)
		Liquid-gas hydrogenation	Highly saturated fuel products
	Solvolysis	Hydrolysis: hydrolysis of post-consumer PET	Terephthalic acid (TPA) and ethylene glycol EG
		Aminolysis: usually reaction of PET with primary amine aqueous solutions	Diamides of TPA, i.e. bis(2-hydroxyethylene) terephthalamide (BHETA)
		Ammonolysis: action of ammonia on PET in an ethylene glycol environment	Terephthalamide
		Methanolysis: degradation of PET by methanol at high temperatures and high pressures	Dimethyl terephthalate (DMT) and ethylene glycol (EG)
		Glycolysis: molecular degradation of PET polymer by glycols, in the presence of trans-esterification catalysts.	Bis (2-hydroxyethyl) terephthalate (in case of PET)

Table 5
Overview of the existing standards in the field of plastics' recycling [17,28, 135–140]. Types of standards: DIN - German standard, EN - European standard, ISO – international, CEN/TR or CEN/TS – technical report or technical specification established by European Committee for Standardization.

Standard	Main points
ISO 15270	Description of operations and terminology for development of infrastructure for various recycling approaches and a sustainable market for recyclates and recyclate-based plastic products.
ISO 14021	Requirements, terminology and general evaluation as well as a verification methodology for symbol and graphics for self-declared environmental claims, like "compostable", "degradable" or "recyclable"
EN 15343	Description of a process required for the traceability of recycled plastics and calculation of recycled content in a given recyclate-based plastic product.
EN 15347	Schema for the characterization of plastic waste to be provided by supplier to a buyer:1. The mandatory data: mass of the batch, color (visual examination), form (chips, film, bottles, etc.), history of the waste (original use, art of collection and treatment after it became a waste), main and all of the secondary polymers present, packaging.2. Optional data: polymer properties, impact strength, mass flow index, Vicat softening temperature, additives, contaminations, humidity, volatile components, ash residues, elongation at break, yield stress, number of volatiles.
CEN/TR 15353 (DIN-Technical report)	Description of a framework for the development of standards for recycled plastics.
CEN/TS 16011 (SPEC 91011)	Description of sampling, specimen preparation, testing methods and documentation for plastic recyclates.
CEN/TS 16010 (SPEC 91010)	Definition of sampling procedures for testing of plastic waste and recyclates during all stages of recycling process.

3.1. Recycling standards on characterization, traceability and sampling

The **Table 5** provides overview of recycling standards, which describe general terminology, characterization, sampling, testing approaches and frameworks for the development of further recycling standards. Three international standards "ISO 15,270 - Guidelines for the recovery and recycling of plastics waste" [28], "ISO 14,021 - Environmental labels and declarations: Self-declared environmental claims" [17] and "ISO 472 - Plastics – Vocabulary" [30] represent the basis for nearly all other recycling standards. These standards define terms like "recyclate", "recycling processes" and further related terms like for example "plastic waste".

Due to the dynamic development of the plastics recycling industry, some of the defined terms must be updated and concretized, in order to prevent their possible misuse in order to meet the recycling targets mentioned in the first section and avoid greenwashing. For example, it is important to ensure that recycling of post-consumer plastic waste is prioritized compared to the recycling of less contaminated post-industrial waste. Post-industrial waste includes rework, regrind or scrap which has been generated in a given production process.

Traceability of recycled content in a given plastic product is one of the further important points. The European standard EN 15343 [135] describes gravimetric approach for the definition of recycled content in a given product and the ISO 14021 [17] defines the use of the corresponding label "Mobius Loop", Fig. 2. However, there is no standardized definition of a recyclate with regard to the minimal content of recycled material in a given plastic product. At the same time, as mentioned above in the case of the chemical recycling, due to the technical features, it is not possible to ensure that a given plastic product contains the recycled content identified on the label. Consequently, there is a demand on update of the existing standards, in order to ensure sustainable and transparent recycling market.

Table 6
Overview of the existing product-specific standards on plastic recyclates [141–146].

Standard	Main points
DIN EN 13430	Specification of the requirements and scope of technologies for packaging, to be classified as recyclable. Description of material recovery criteria with regard to chemical composition, suitability for certain recycling approach and corresponding environmental impacts.
DIN EN 13437	Description of criteria for a recycling of diverse packaging materials, corresponding recycling process steps and material flow for various packaging materials including plastics.
DIN EN 17410 (Draft)	Description of the existing quality control, traceability and testing processes for recycled PVC for use in window and door profiles, including corresponding material requirements including origin, waste art, ash residues, bulk density, color (visual examination), foreign substances, grain size distribution, form, Vicat temperature, e-modulus, strength of the welded corners. Definition of guidelines for recyclability with regard to contaminations, which would affect the recycling after the use stage.
ISO 12418–1	Description of a designation system for all post-consumer PET bottle recyclate forms including powder, flakes or pellets on appropriate levels of the designatory properties including intrinsic viscosity, level of contaminations, water content, bulk density, recycling process used, form of the product, mesh size used in the case of pellet extrusion, filler, intended application and / or processing method, information regarding food packaging, color, etc.
ISO 12418–2	Definition of testing methods to be used for the determination of the properties of PET bottle recyclates, for example, presence of various impurities and contaminations
DIN CEN/TS 14541(DIN SPEC 16498)	Representation of characteristics for utilization of non-virgin PVC-U, PP, PP and PE materials
DIN CEN/TS 16861 (DIN SPEC 91009)	Definition of markers and analysis processes verifying purity of PET recyclates for food industry (merely as an additional guideline for Challenge Test of European Food Safety Authority (EFSA)

3.2. Product- and application-specific recycling standards

Further category of the European standards can be classified as product-specific standards, which specify properties of the recyclates, which are important for a certain product types manufactured in a large volume such as plastic packaging [141,142], windows or doors made of polyvinyl chloride (PVC) [140,143] or PET bottles [144–146], Table 6. Timely introduction of these standards promoted implementation of closed-loop recycling in these fields. At the same time, there are still a lot of plastic products, for which there is no standards for example lightweight applications like wind energy, transport, aircraft, sport, and leisure, etc.

3.3. Polymer-specific recycling standards

The **Table 7** summarizes polymer-specific types of European recycling standards. Currently, there is no polymer-specific types of standards at the international standardization level. The existing standards are limited to polystyrene (PS) [147], PE [148], PP [149], PVC [150] and PET [151]. All of the polymer-specific standards are buildup in the same way and include mandatory and optional data. This means that if a supplier aims to characterize recyclate according to the corresponding standard, the mandatory data must be specified. At the same time, the optional data can be specified, if this would increase the price of the recyclate. Furthermore, the standards allow identification of further data. As an example, molecular mass defined via K-value in the case of the PVC standard is neither mandatory nor optional data. However,

Table 7
Overview of the mandatory and optional data required for the characterization of polymer recyclates according to the existing European standards and the corresponding testing methods [147–151] M – mandatory data, O – optional. Modified overview based on previous publication[[152]].

Property	Measuring method	EN 15342	EN 15344 (draft)	EN 15345	EN 15346	EN 15348
		PS	PE	PP	PVC	PET
Original use	To be stated by supplier	O				
Form	Visual examination	M	M	M	M	M
Recyclate content	EN 15343			O		
Color	Visual examination	M	M	M	M	M: Visual examination O: EN ISO 11664-4
Grain size	ISO 22498	M: Method according to the grain art and grain size range	M			
Grain size distribution	Standard-specific test				M: Annex D and E	M: max. grain size
Bulk density	Standard-specific test	O: Annex A	M: Annex B	O: Annex A	M: Annex B	
Density	EN ISO 1183	O: EN ISO 1183-1 or process A	O	M: EN ISO 1183-1 or process A	O: EN ISO 1183-1 or process A	
Proportion of fines	Standard-specific test					M Annex A
Filtration rate	Mesh size	O	O	O		
Filtering capability	Standard-specific test					O: Annex E
Melt mass-flow rate	EN ISO 1133	M: EN ISO 1133, condition H	M	M: EN ISO 1133, condition M		O: ISO 1133-2
Intrinsic viscosity	ISO 1628-5					O
Pourability	EN ISO 6186				O	
Vicat softening temperature	EN ISO 306	M: EN ISO 306, process A			O: EN ISO 306, process B50	
Heat resistance	ISO 182-1, EN ISO 182-2, -3, -4				O	
Impact strength	EN ISO 179-1, -2, EN ISO 180	M	O	M		
Yield stress	EN ISO 527-1 or -2	O	O	O	O	
Elongation at break	EN ISO 527-1 or -2	O	O	O	O	
Bending properties	EN ISO 178	O		O		
Hardness	ISO 868				M (by PVC-P)	
Presence of foreign polymers	FTIR or DSC		M: (Presence of PP and foreign polymers)	O		
Presence of modified additives	To be stated by supplier	O				
Foreign substances / contaminations	Standard-specific test		M: Process A, B, C or D		M: Annex C	
Content of volatiles	Standard-specific approach	O: Mass loss at 200°C		O: EN 12099 or other	O: EN ISO 1269	
Residual humidity / water content	EN 12099	O	O		O	M: Annex B or EN ISO 15512
Ash content	EN ISO 3451	O	O	O	M: EN ISO 3451-5 or Process A	
PVC content	Standard-specific test					M: Annex C
Polyolefin content	Standard-specific test					M: Annex C
Other residual content						O: Analysis using one of the suitable methods: FTIR, DSC, XRF, etc.
Alkalinity	Standard-specific test					O: Annex D
Suitability for processing of PVC recyclates – through calendering / – through extrusion	Standard-specific test				O: Annex F / Annex G	

numerous technical data sheets for virgin and recycled PVC include it, since due to historical development this information is important for manufacturers. Similarly, as in the case of the above-mentioned standards, polymer-specific standards represent a guideline, which aims simplified and transparent communication between contractors.

Furthermore, methods used for determination of the mandatory and optional data must be considered. For the definition of material properties like viscosity, Vicat softening temperature or mechanical properties the data must be defined according to the procedures, Table 7. However, in the case of optical or morphological properties like color or form the definition is provided according to visual examination, which results in subjective results. Especially, color of a recyclate is an important issue. Firstly, color shades are omitted during the visual examination of the plastic recyclate, but they are important during the manufacture of plastic products. Secondly, color deviation can be considered as one of the factors limiting closed-loop recycling. Finally, improvement of color is possible only in certain cases, mainly in the case of darkening. The vice versa case, where the color of the material must be lightened is technically challenging and associated with higher costs. Moreover, Fourier-transform infrared spectroscopy (FTIR) and differential scanning calorimetry (DSC) are most commonly used for the analysis of the chemical composition [148,149]. However, due to the limited detection limit these techniques are generally not suitable for the identification of additives such as stabilizers or antioxidants present in low concentration.

If plastic recyclates are aimed to substitute primary plastics in as much applications as possible, the data provided in TDS for recyclates should be at the same precision and reliability level as for the virgin plastics. Currently, technical data sheets provided for the plastics recyclates represent very differing amount of information data and quality, i. e. precision including used testing methods and possible deviations [152]. At the same time, novel quality specifications and guidelines are already in developmen [153].

To sum up, the already existing standards represent the very first basis for the introduction of a sustainable CEM in the plastics industry. At the same time, due to the dynamic development of this field, these standards need to be updated in terms of the quantity of data about recyclates as well as the concretization of the data source and testing methods for some properties. , These updates can promote the establishment of a global supply chain for the plastic recyclates.

4. Recycling of plastics – market situation

In 2018 the global plastics production volume reached 360 million tons including 62 million tons in Europe, [154]. This value includes thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants and PP-fibers, but excludes PET-, PA- and acrylic fibers. Packaging and building and construction represent 39,9% and 19,8% of the plastic demand in EU [154]. PE and PP as well as PET and PS are mainly used in packaging, while PVC is predominantly used in building sector, **Fig. 5**. As a result, these materials also represent the major portion of the generated plastic waste worldwide. [156–160]

At the same time, the life time of the plastic products in the packaging and building industries are different [154]. Therefore, the amount of generated and collected plastic waste does not necessarily correlate with the annual demand on plastics. With regard to the lifetime, it is possible to categorize plastic products into three categories: short-life, like packaging, middle-life including products for agriculture, electronics or automotive and long-life, for example for building and construction. The consumption volume and the volume of produced waste

Fig. 5. Plastics demand by segments and polymer types in 2018. Total 51.2 mt data for EU, Norway and Switzerland [154]. Reproduced with permission from PlasticsEurope.

in one year differ strongly for these three groups: produced volume of packaging results in more than 80% of waste, while amount of durables (middle- und long-life products) results in less than 35% of the waste [11]. As a result, there is a gap between plastic consumption and plastics waste generated.

Fig. 6 represents the global plastic material flow within the life cycle of plastics products [11].According to the survey around 250 million tons of plastics waste were generated worldwide in 2018. This value is represented in Fig. 6 as “waste collection” and “unknown plastic waste”. At the same time, only approx. 175 million tons, i.e. 70% of the plastic waste were collected by various waste collections systems and recycled, landfilled or energetically valorized [11]. The remaining 30% were improperly disposed or leaked and represent unknown plastic waste. Due to the import and export of materials at various stages of the life cycle, it is not possible to ensure that a product, which is suitable for recycling in one country will not be inappropriately disposed in another country. Around 30 million tons of plastic waste were generated in Europe, Norway and Switzerland, while 29,1 million tons were collected and around 9,4 million tons of the collected plastics waste were recycled on site or in Asian countries [11].

The use of recyclates in plastic products increases steadily. The recycling capacity (output) was 1,1 million tons in 2019, which is 28% higher than that in 2018 [21]. The recycled plastics are already used industrially in packaging, building and construction, automotive, electrical and electronic products, household as well as leisure and sport, furniture, agriculture, and other applications [155]. For example, the global recycled content in packaging grew by 22% from 2018 to 2019 [21]. Particularly, in 2019 the collective worldwide recycled content in plastic packaging was 6,2% [21]. Despite of the existing technological and standardization challenges in the field of plastics’ recycling, this is very promising development. Furthermore, various regional activities promote use of recyclates in plastics industry. For example, the European Strategy for Plastics in a Circular Economy based on design and production meeting the needs of reuse, repair and recycling presumes following modifications by 2030 [162]:

– Plastic products should be reusable or suitably designed for a cost-effective high-quality recycling.
– High level of efficiency of separate plastic waste collection systems enabling recycling of more than 50% of plastic waste generated in Europe.
– Fourfold increase of sorting and recycling capacity compared to 2015, leading to the creation of 200 000 new workplaces.
– Establishment of integrative value chains promoting close cooperation between chemical industry and plastic recyclers. Broadening of application fields for recyclates and substitution of substances hindering recycling processes.
– Establishment of a stable growing market for recycled and innovative plastics including a fourfold growth in demand for recycled plastics in Europe and security for workplaces.
- Development and use of innovative materials and alternative feedstock for plastic production compared to the non-renewable alternatives.

Implementation of this strategy requires involvement of all stakeholders: local waste management authorities, collection companies, sorters, recyclers, plastic product manufacturers, consumers, waste disposers responsible for landfill and incineration as well as standardization organizations and academia.

This review presents results of the first global surveys on market data about plastics recycling available [11],[154],[155]. It is important to consider, that the data collection is challenging due to great differences in regional regulations, economics and priorities for waste management [11],[155].

5. Conclusion

Growing environmental awareness and legal regulations have pushed implementation of Circular Economy Model in the plastics industry. In order to meet this implementation requirement, various scientific, standardization and legal activities have been undertaken. This paper reviewed currently available material recycling technologies along with further plastic waste treatment options like biodegradation

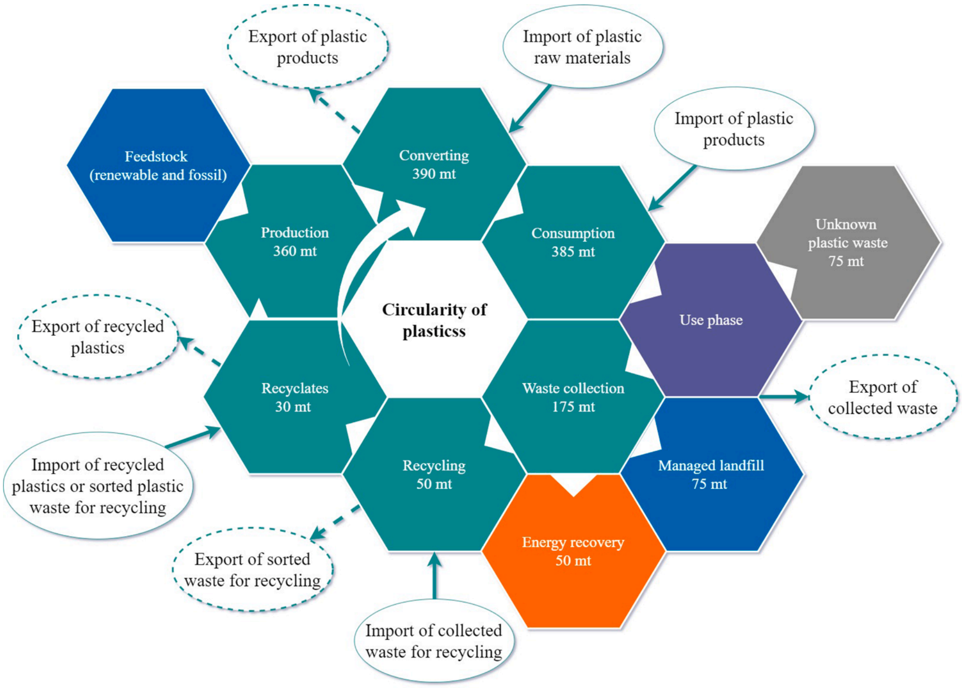

Fig. 6. Circularity of plastics (own illustration based on literature data [11]).
Note: mt – million tons.

and energetic valorization. Furthermore, it reviewed existing standards and market data.

The majority of the research studies reviewed in this work have focused on mechanical recycling technology and include development of application-oriented plastics and composites based on recyclates. Especially recycling of polyethylene and polypropylene from packaging is in the foreground. Promising results regarding improvement of mechanical properties of recycled plastics using compatibilizers have been reported. Furthermore, recent studies have contributed for the understanding of multiple recycling of plastics, especially the relationship between processes at the molecular level and mechanical performance. However, transfer of these findings into practical applications has only limited success so far. The main challenge is the absence of a global waste management system and a limited number of international recycling standards. As a result, regional regulations and standards cannot ensure effective and economic recycling of plastic products, especially with regards to the global plastic material flow.

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Declaration of Competing Interest

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