# A Systematic Review on the Materials used in Medical Plastic Packages and the Influence of Recycling on the Mechanical Properties of Plastics

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**ABSTRACT**

**Background** Disposable packages account for 50% of medical plastic waste. Recycling could be a practical approach to reducing medical waste. This review aims to research what materials are used in medical plastic packages and the influence of recycling on the mechanical properties of these materials. Two separate systematic reviews are completed to answer the research questions.

**Method** A systematic approach based on the PRISMA guidelines 2020 was followed. Scopus and Web of Science databases were used to conduct the research. All reports published on the subject were extensively scanned to answer the defined research questions. The studies included in the review were based on predetermined inclusion and exclusion criteria. The included articles were used to synthesize the findings of the study.

**Results** The first systematic review provided 1823 articles, of which 37 were included in the study. The search yielded monopolymer, multilayered, paper-plastic, and Tyvek-plastic packages. Materials encompassed in medical packaging included polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), polyvinyl chloride (PVC), polystyrene (PS), nylon6, ethylene vinyl alcohol (EVOH), chlorotrifluoroethylene (CTFE), polyester, and polyamide (PA). The second systematic review provided 434 articles, of which 16 were included in the study. The search yielded articles related to the mechanical properties of virgin and recycled components, blends and their constituents, homogeneous and heterogeneous blends with increasing ratio of recycled content, and properties after multiple extrusions. The mechanical properties of blends strongly depended on their composition. A higher young's modulus and tensile strength appeared to be related to a higher crystallinity and lower elongation at break with decreasing molecular weight.

**Conclusion** Recycling processes should be the first deliberation for hospital waste management. Medical packages which include one polymer can be recycled in neat form, whereas recycling multilayer packaging is more challenging due to the different components. Mechanical properties differ per application; therefore, it is essential to research the effect of recycling on medical plastic packages.

**Keywords** *medical packaging, plastic recycling, mechanical properties, circular economy*

## INTRODUCTION

Over the past century, plastics have facilitated considerable advances in human society (North & Halden, 2013). Their multiple functionalities, low cost, easy processability, and unique properties (thermal, mechanical, optical, and electrical) have allocated their success and made them appealing to replace traditional materials such as wood, glass, metal, and ceramics (Haned et al., 2018; Horodytska et al., 2018; Nomura et al., 2020; North & Halden, 2013; Rosato, 2011). Around the world, 380 million tons of plastics are produced. Notably, 42% is used for applications such as packaging (Nomura et al., 2020), making them the most significant end-use for plastics despite their environmental pressure (Rosato, 2011).

We live at a time where environmental issues and public health are converging. Climate change, especially global warming, is increasing poor health worldwide (Nomura et al., 2020). Perversely, environmental problems are related to health care facilities, as they constitute a great source of pollution across the globe (Shinn et al., 2017). Worldwide, the global market share of medical device packaging is around $ 22 billion a year and is expected to grow 5,9% annually (Đuzelić & Hadžalić, 2019; Kwon et al., 2017). This growth is related to continuous technological developments in medical product industries, preference for disposable medical devices, increasing aging population, and other social-economic factors (Gill et al., 2022; Jang et al., 2006; Kwon et al., 2017; Rosato, 2011). Plastics used for single-use, including packaging, are the most significant sources of pollution. Therefore, reducing their carbon footprint is crucial (Martin et al., 2021; Vidakis et al., 2021).

Disposable medical packages account for 50% of all plastic medical waste (Healthcare Plastic Waste, 2021). Much of the waste generated in healthcare facilities is comparable to household waste (Shinn et al., 2017). However, health care facilities define this as regulated medical waste (RMW), necessitating specific waste treatment (Jang et al., 2006; North & Halden, 2013; Shinn et al., 2017; Stoian et al., 2019).

Globally, the interest in recycling or reusing medical waste is expanding (Van Straten et al., 2020; Pinjing et al., 2013). Hospitals could be a valuable source for raw material extraction from the stance of urban mining since hospitals' supplies are high material quality (Van Straten et al., 2021). Recycling plastics could effectively reduce medical waste (Shinn et al., 2017; Stoian et al., 2019). It would prolong the life cycle of plastics and lower environmental concerns (Stoian et al., 2019; Uehara et al., 2015).

Recycling various materials to improve properties and further use is becoming a predominant area of research (Dobránsky et al., 2021). A literature review was performed to map the research on the recyclability of medical plastic packaging, identify existing literature gaps, and make recommendations for future work. Two separate systematic reviews were completed to answer the research questions. The first systematic review was guided by the research question: What materials are used in medical plastic packages? The second systematic review was directed by the research question: What is the influence of recycling on the mechanical properties of plastics?

Literature research: materials used in medical plastic packages

## METHODS

A systematic approach was followed based on the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) guidelines 2020 (Page et al., 2021). The search was completed methodically and efficiently, while the most relevant information on medical plastic packaging was found. Each search plan consisted of analyzing the research topic, formulating search queries, and determining what type of information was necessary. The reports included in the review were based on identified inclusion and exclusion criteria used to synthesize study findings.

### Eligibility criteria

Plastic healthcare packaging can be separated into two groups: medical and pharmaceutical. Products included in medical packaging include medical devices such as syringes, needles, catheters/tubing, sutures, dressing, and gloves (Czerniawski, 1990). Products included in pharmaceutical packaging include blister packs for drugs, vials, and bottles (Rosato, 2011). Records were included in the study if they considered medical packaging and researched the polymer type. Articles from any geographic setting were accepted for inclusion. Additionally, studies on the topic were also contemplated for inclusion. Records were excluded when they focused on the materials in food packaging, medical devices, biocompatible packaging, or disregarded the polymer type.

Included types of packages

A brief explanation of the types of packages considered eligible for inclusion will be outlined. The included studies were assembled into monopolymer, multilayered, paper-plastic, and Tyvek-plastic groups. Monopolymer packages consisted of one polymer, while multiple polymers were incorporated into multilayered packaging. Besides the polymeric packaging system, various packages mentioned the sealing material. The sealing material encompassed paper or Tyvek.

### Information sources

The research was conducted in Scopus and Web of Science multidisciplinary databases without time constraints. The search across all databases resulted in identifying 1806 records, seen on the top left in Figure 1. Additional records were identified through other sources. A secondary search procedure included going through reference lists of relevant articles. The additional search yielded the discovery of 17 records, seen on the top right in Figure 1. The final search was run on March 7, 2022.

### Search strategy

The writer of this review completed an iterative process of finding, refining, and improving alternative search terms. A search plan based on the structure of the TU Delft library was assembled (*"Making a search plan"*, 2021). The final search string for Scopus and Web of Science was composed of synonyms and keywords of "material," "package," "environment," "composition," "medical," "waste stream," and "plastic." The final search string can be viewed in Table 1 of the Appendix.

### Selection process

All articles were selected and imported into the bibliography manager EndNote X9. For each screening level, a new library was created to keep track of the number of records complying with the inclusion and exclusion criteria. Records in the first library were screened for title and keywords relevance. In the second library, records were screened on the abstract. Reports considered relevant were imported into the third library for full-text screening. The final library contained the reports included in the study. For each screening level, the writer of this review decided whether a study met the inclusion criteria. The identified references will be discussed in the results section.

### Data collection process

The data collection process involved extracting relevant information from the studies included in the systematic review and presenting it in a logical form (Charrois, 2015). The author, year of publication, and polymer type were inserted into an MS Excel spreadsheet.

This review presents the retrieved information from the full-text articles in tabular form. One reviewer collected the data from each report and developed a table for each category. In the results section, the content of each group will be discussed.

## RESULTS

### Study selection

The current literature study identified 1806 articles through database searching and 17 through other sources. Figure 1 details the process of conducting a literature search and selecting reports. After removing the duplicates, 1272 articles remained. The title, keywords, and abstracts were reviewed against the inclusion criteria and were excluded when they did not meet the eligibility criteria. Screening the title and keywords excluded 960 articles from database searching and four from other sources. Consequently, 152 and eight articles were not retrieved when screening the abstracts of reports obtained from the databases and other sources, respectively. The reviewer assessed the full text of 148 remaining articles. For reasons shown in Figure 1, an additional 108 articles were removed. Finally, 35 articles from database searching and two articles from other sources were considered applicable for this systematic review.

## Data presentation

A summary of the results is presented in the section synthesis of results. The final articles were categorized according to the type of packaging: monopolymer, multilayer, paper-plastic, and Tyvek-plastic. If an article covered several groups, the findings were presented in all tables related to the categorized group.

Tables 2-5 in the Appendix summarize the polymer type in the medical plastic packages. Polyethylene (PE) was generally used in two forms, high-density polyethylene (HDPE) and low-density polyethylene (LDPE). The specified PE type is mentioned in the PE column if an article stated the form explicitly. The tables include the author and year of publication for each article.

## Synthesis of results

Table 2 summarizes the materials found in monopolymer medical packaging. Polypropylene (PP) and polyvinylchloride (PVC) occurred most frequently, followed by polyethylene (PE), polyethylene terephthalate (PET), polystyrene (PS), nylon 6, and polyamide (PA).

Table 3 summarizes the materials found in multilayered packaging. The packages consisted of binary and tertiary constituents and the most common form included layered PE/PP and PE/PET.

Table 4 is devoted to materials in paper-plastic packages. PP, PE, and polyester were the most frequent polymers in monopolymer packages. In multilayered packages, the combination of PE with PET or polyester had the highest occurrence. Most paper-plastic packages occurred in multilayered form.

Table 5 summarizes the materials found in Tyvek-plastic packages. PET was the most prevalent polymer in monopolymer packaging and PE/PET in multilayered packaging. An equivalent amount of monopolymer and multilayered packaging was found.

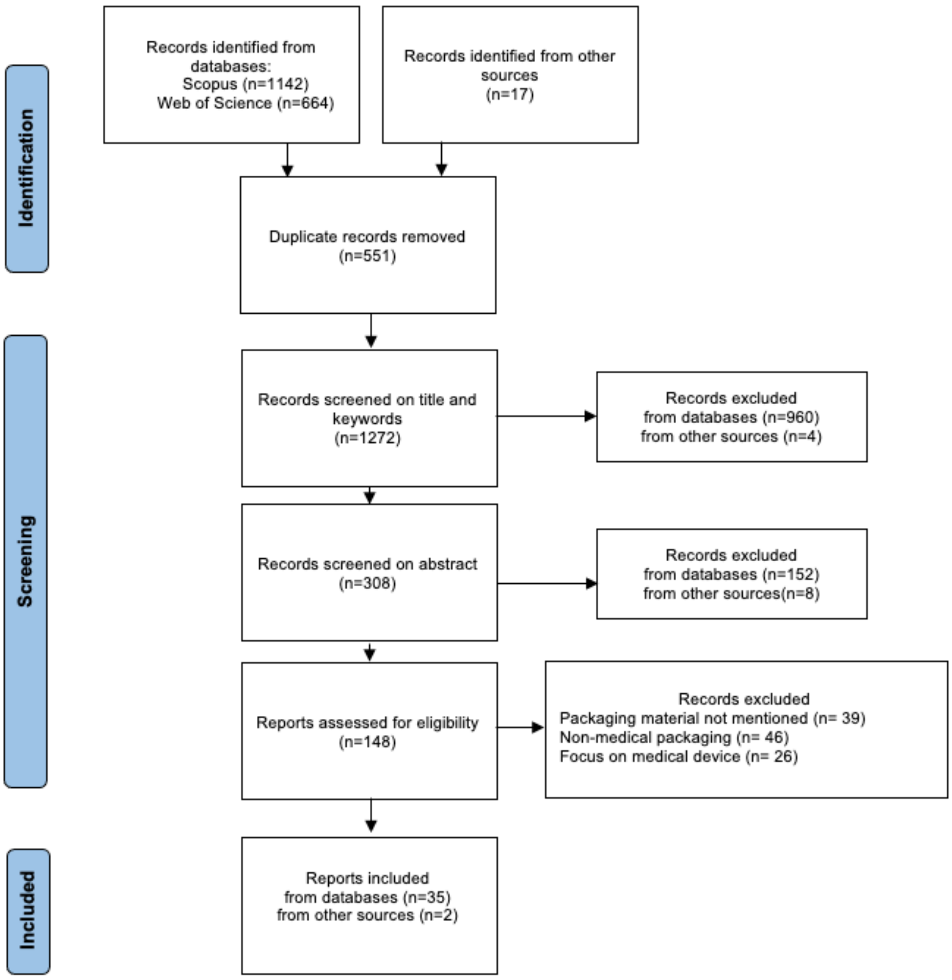


Figure 1. PRISMA flowchart

## DISCUSSION

This systematic review presents an overview of the materials discovered in medical plastic packaging. The findings will be highlighted below, followed by the limitations and conclusion of the current study.

### General interpretation

Medical devices generally have polymeric packaging systems (Guyer & Zednik, 2010). A predominant requirement is that the material provides a bacterial barrier, guarantees sterility, and prevents microorganisms from infiltrating the material (Dixon et al., 2007; McKeen, 2017). Furthermore, the packaging must resist various environmental and mechanical stresses such as dropping, scratching, vibration, shipping, thermal shock, thermal recycling, and radiation (Guyer & Zednik, 2010).

Studies on the material of medical plastic packaging consisted of one or multiple polymers in layered form. In several studies, the sealing material was mentioned. Sealing was the most crucial manufacturing step for medical packaging (Dixon et al., 2007). Paper and Tyvek were often designed in the packaging of medical devices that underwent sterilization (Đuzelić & Hadžalić, 2019). Tyvek was a more costly alternative than paper (Czerniawski, 1990). Nonetheless, it came as a substitute for paper as the material offers superior strength (Dixon et al., 2007).

The medical packages found in this review primarily incorporated one polymer. Based on the findings of this systematic review, PP was the leading material in monopolymer packaging, succeeded by PVC and PE. In multilayered packaging, the qualities of different materials were combined, providing a light barrier, gas barrier, mechanical support, and sealability (Mulakkal et al., 2021). PE/PET was the leading composition in multilayered packaging, followed by PE/polyester. The layered structure created customized property profiles (Kaiser & Ginzinger, 2021). PVC, PS, and nylon 6 were undiscovered in multilayer packaging, while polyester was identified more often in multilayer packaging than monopolymer packaging.

Although 37 studies on medical plastic packages were found, during the search across databases, it became apparent that it was challenging to find articles that emphasized medical plastic packages and mentioned the polymer type. An example is provided by Lee et al. (2002) and Shinn et al. (2017). Lee et al. (2002) researched the quantity of medical packaging generated per year and mentioned the relative percentage compared to other medical plastic waste, yet omitted the specific material in the medical package. Another example from Lee et al. (2002) is the division of waste into the categories "IV bag," "Medical," "Film," "Patient kits," "Disposable gloves," and "Other plastics," excluding the category "Packaging." Shinn et al. (2017) discussed the weight of components from three operations. The components were grouped into "Cardboard," "Plastics," "Clear wrap," "Blue wrap," and "RMW." Nevertheless, the polymer type was not acknowledged within the plastics group.

### Limitations

The findings of this review must be considered with some limitations.

It was decided only to extract the polymer type from the articles, which aligned with the research question. However, a more extensive description, such as the medical packaging application (e.g., needle or catheter), would be interesting from a recycling perspective as the mechanical properties differ per application (Dobránsky et al., 2021; Stoian et al., 2019). Unfortunately, it was beyond the scope of the first systematic review to perform a more comprehensive synthesis of the included literature.

Another study limitation is that the search is completed in two databases. The rule of thumb for systematic literature research is that more than two databases must be used (Charrois, 2015). Therefore, it is seen as a limitation that an additional database was not added as this might enable a more extensive overview of the materials. Given the limited time available, the search was not performed in an additional database.

Finally, the selection of studies in the current review was carried out by one reviewer. In contrast, in a systematic review, the eligibility of promising studies must be examined independently by at least two researchers to decrease the possibility of bias. A comparison would be made of the included studies assembled by the two reviewers, and when disagreements occur, this would be resolved through discussion or consensus with a third researcher (Charrois, 2015). Considering only one reviewer defined the inclusion and exclusion criteria for the study selections, this can be seen as a limitation as relevant articles may be missed.

### Conclusion

The study's objective was to research what materials are used in medical plastic packages. Medical packaging can be divided into monopolymer or multilayered packaging. The polymeric packaging material in monopolymer packaging include PP, PE, PVC, PET, PS, PC, nylon 6, and PA. The materials found in multilayer packaging include PP, PE, PVC, PET, PA, nylon 6, polyester, ethylene vinyl alcohol (EVOH), and chlorotrifluoroethylene (CTFE) Similarly, several packages include a paper or Tyvek sealing layer. Future studies should include the application of the package from a recycling perspective.

### Literature research: influence of recycling on the mechanical properties of plastics

The polymeric materials established in the first systematic review will be used to research the influence of recycling on the mechanical properties of plastics. Background information is provided on the different recycling methods for monopolymer and multilayered packaging.

## INTRODUCTION

Plastics can be categorized into thermoplastics and thermosets. Thermoplastics consist of linear molecular chains which soften when heated and harden when cooled. These polymers are considered recyclable. On the contrary, thermosets are referred to as irreversible polymerization and become insoluble and infusible when cured by heat or chemical reaction (Grigore, 2017). Recycling of thermoplastics can be done through mechanical recycling, chemical recycling, or energy recovery (Grigore, 2017; Horodytska et al., 2018). During the physical process of mechanical recycling, plastics are separated, washed, ground, re-granulated, and melted to create new products by extrusion while the structure of the polymer remains unchanged. The primary polymer processing technique is the injection molding process. Chemical recycling breaks down the polymer structure into monomers through glycolysis, hydrolysis, and pyrolysis. Energy recovery of plastics is made through incineration. However, this process leads to toxic substances like carbon dioxide being released into the atmosphere (Dharmaraj et al., 2021; Grigore, 2017; Horodytska et al., 2018; Martin et al., 2021).

To achieve preferable material properties, blending the reprocessed material with virgin material is possible. A homogeneous blend is created when solely one material is processed. In addition, a heterogeneous blend is created once multiple polymers are blended. The composition of a blend is critical in recycling. Properties of blends tend to decline after each recycling cycle due to degradation and heterogenicity (Dharmaraj et al., 2021; Mulakkal et al., 2021; Van Kets et al., 2019). Compatibilizers can be added to enhance mechanical properties and adhesion between polymers (Cabrera et al., 2021; Van Kets et al., 2019). However, this can create new issues for recycling blends in the future (Mulakkal et al., 2021). Recycling multilayered films is more challenging than monopolymer films due to the inhomogeneity, incompatibility, and melting points of polymers (Cabrera et al., 2021; La Mantia, 1992; Nomura et al., 2020). Several approaches focus on processing the different materials in multilayers together, others on separating them through selective solvents or delamination (Kaiser & Ginzinger, 2021). The recycling of monopolymer packaging leads to homogeneous blends, whereas the recycling of multilayered packaging leads to heterogeneous blends. Therefore, the current systematic review emphasizes both blend compositions.

This study will focus on the influence of mechanical recycling on the mechanical properties of homogeneous and heterogeneous blends. The mechanical properties will be compared before and after recycling, with an increasing ratio of recycled content and after multiple extrusion cycles without the addition of compatibilizers.

## METHODS

A systematic literature review following the PRISMA 2020 guidelines was performed (Page et al., 2021).

### Eligibility criteria

Articles were included in the study if they considered thermoplastics and emphasized the mechanical properties after recycling. The suitable materials included the thermoplastics found in the first literature research. The mechanical properties must focus on the young's modulus, strength, and elongation. In addition, reports from any geographical area and reviews on the topic were considered eligible for inclusion. Records were not retrieved when the material was outside the scope of the study, fiber-reinforced, and excluded mechanical performance of recycled material. The classification of materials and definitions of the mechanical properties used in the articles will be briefly explained below.

#### Classification materials

The types of thermoplastics included in this review were PP, PE, PET, PVC, and nylon6. The materials could be categorized into crystalline, amorphous, or semi-crystalline thermoplastics (Grigore, 2017). Crystalline thermoplastics were presented in a regular arrangement containing translucent molecular chains. PP and PE were associated with this group. The molecules in amorphous polymers were randomly arranged. PVC belonged to the amorphous polymer group. Semi-crystalline polymers possess crystalline as well as amorphous polymer properties. This group was represented by PET and nylon6 (Grigore, 2017).

#### Definitions mechanical properties

Uniaxial tensile tests were performed to assess the mechanical properties. A specimen was elongated until fracture resulting in a stress-strain curve. In Figure 2, a typical stress-strain curve is presented. The definitions of measurement points A-K included in this review can be viewed in Table 6.

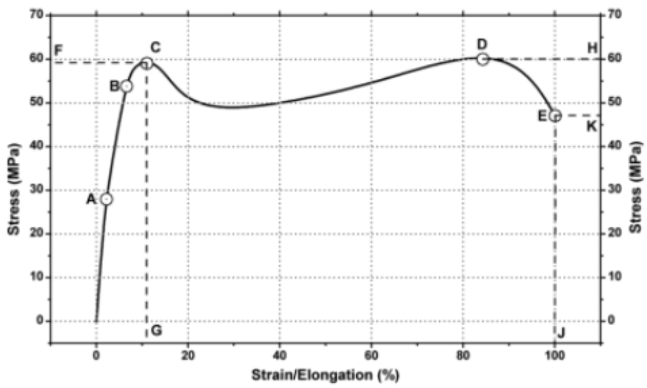


Figure 2. Typical stress-strain curve (McKeen, 2017)

**Table 6** Definitions of tensile and elastic properties (McKeen, 2017)

| Property | Definition |
|---|---|
| Elastic modulus (A) | Ratio of stress to strain in the elastic region. |
| Tensile strength at yield (F) | Tensile stress corresponding to yield point |
| Tensile strength at break (K) | Tensile stress corresponding to the point of rupture |
| Tensile strength, ultimate (H) | Highest tensile stress before failing |
| Elongation at yield (G) | Tensile elongation corresponding to yield point |
| Elongation at break (J) | Tensile elongation corresponding to yield point |
| Additional information | |
| "B" | Elastic limit, after this point, permanent deformation |
| "C" | Yield point, after this deformation occurs, without an increase in strain |
| "D" | Ultimate strength, maximum stress on the curve |
| "E" | Breakpoint |

### Information sources

The search for this systematic review was conducted in the databases Scopus and Web of Science without time constraints. The search across the databases resulted in the identification of 415 records, seen on the top left in Figure 3. Identification of supplementary records was accomplished through other sources and resulted in the addition of 19 records, as seen on the top right in Figure 3. The secondary search procedure included checking if authors had published more relevant articles and reviewing relevant studies' reference lists. The final search was run on April 6, 2022.

### Search strategy

The writer of this review completed an iterative process of searching, refining, and improving the alternative search terms. The final search string was encompassed by synonyms or keywords of the concepts "Material," "Recycling," and "Mechanical properties." The final search string can be viewed in Table 7 of the Appendix.

### Selection process

All identified records were inserted into the bibliography manager EndNote X9. For each screening level, the writer of this review decided whether a study was relevant. Articles were first screened on the title and keywords, followed by a screening of the abstract. The full text of reports was assessed for eligibility when the articles seemed relevant. A new library was made for each screening level to keep track of the records corresponding to the inclusion and exclusion criteria. Finally, the included studies were selected based on identified eligibility criteria.

### Data collection process

The data collection process involved retrieving relevant information from the studies found in the literature and presenting it in a logical form. Data concerning the author, year of publication, and values of the mechanical properties were inserted into an MS Excel spreadsheet. Young's modulus, tensile strength, and elongation were the primary summary measures. The ultimate tensile strength, tensile strength at yield, and tensile strength at break were all examples of tensile strengths included in the study. Elongation could include elongation at break and elongation at yield. A summary of the results is provided in tabular form.

The writer of this review developed six tables, and relevant figures were extracted from articles after screening the full text.

## RESULTS

### Study selection

The current literature study identified respectively 415 and 19 articles through database searching and other sources. A total of 301 records remained after removing the duplicates. Titles and keywords were evaluated against the inclusion criteria excluding 185 citations from database searching and four from other sources. The remaining records were screened on their abstracts, excluding 49 and seven articles from databases and other sources, respectively. The writer of this review assessed the eligibility of 56 full-text reports. For reasons shown in Figure 3, 39 articles were not retrieved. Finally, 12 articles from database searching and four from other sources were deemed satisfactory for this systematic review.

### Data presentation

A summary of the results, along with the figures and tables, is presented in the section synthesis of results. The final articles were categorized according to the type of blend, namely homogeneous or heterogeneous. Within each category, the mechanical properties were compared at three levels. A comparison was made between the mechanical properties of virgin and recycled material, a blend with an increasing ratio of recycled content, and after multiple extrusion cycles.

A table summarizing the included articles' mechanical properties was made for each level of homogeneous and heterogeneous blends. The measurement point was estimated when articles only provided a figure of the mechanical property. In the tables, an asterisk (*) was placed behind the value when the property was estimated from a figure. A high bar (-) was placed in the summary table when the article excluded the property's value.

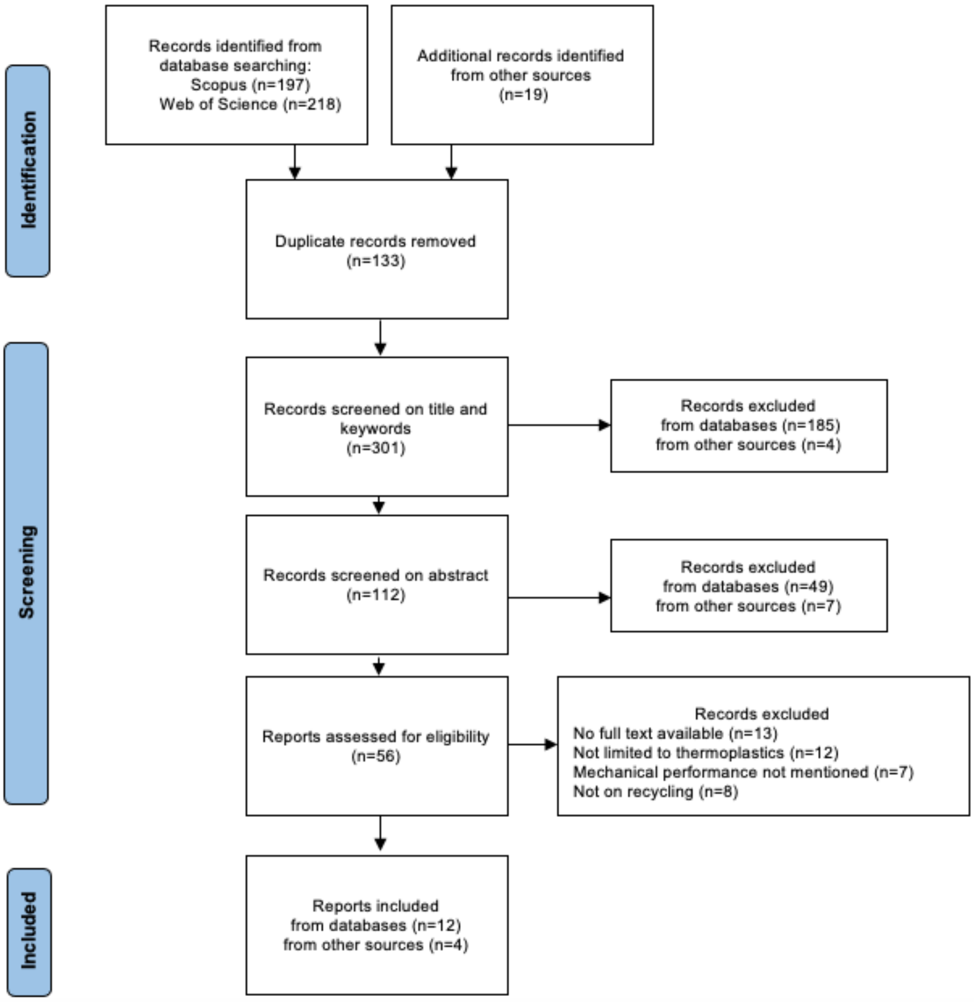


Figure 3. PRISMA flowchart

Tables 8-13 in the Appendix summarize the young's modulus, ultimate tensile strength, tensile strength at yield and break, and elongation at yield and break. The tables were completed as much as possible. The author and year of publication of the full-text articles were included in the table. If an article covered multiple categories, the findings of the mechanical properties were included in all related tables.

## Synthesis of results

The mechanical properties of recycled homogeneous and heterogeneous blends will be addressed in this section.

### Homogeneous products

*Virgin versus recycled material*

Three articles compared the mechanical properties of virgin and recycled material. The materials included PVC, HDPE, and LDPE. Table 8 summarizes the young's modulus, tensile strength at yield and break, and elongation at yield and break. Recycled PVC appeared to have a lower young's modulus and a higher elongation at break compared to virgin PVC. The other properties remained moderately constant when recycled (Ma & LaMantia, 1996). Recycled HDPE showed an increase in young's modulus, a slight increase in the tensile strength at yield, and a decrease in the elongation at break (Kukaleva et al., 2003). Finally, the young's modulus and tensile strength at break of LDPE decreased when recycled, whereas the tensile strength at yield and break and elongation at yield contained similar values (Kaiser & Ginzinger, 2021).

*Blends with increasing recycled content*

The recycled content increased from 0-50% for the PVC blend and from 0-100% for the nylon6 and PP blends.

Ma and LaMantia (1996) proved that when the recycled content of PVC increased, the young's modulus and tensile strength at yield and break decreased, while the elongation at break increased (Ma & LaMantia, 1996). In Table 9, the mechanical properties of PVC can be seen.

Scaffaro and La Mantia (2002) demonstrated that the highest young's modulus is achieved at a mix ratio of 75% recycled nylon6, while the lowest elongation at break is realized in this composition. The ultimate tensile strength remained constant over all blend compositions. Table 9 provides the values of the mechanical properties for the nylon6 blend.

Three articles focused on PP blends. In Stoian et al. (2019), the young's modulus and tensile strength at break decreased as the recycled content of PP rose. The elongation at break increased to 90% recycled content, after which the value decreased (Stoian et al., 2019). In Dobránsky et al. (2021), the tensile strength at yield and break remained moderately the same. The elongation before break yielded similar values, whereas the elongation after break decreased as the recycled content increased (Dobránsky et al., 2021). In Van Straten et al. (2021), the young's modulus and ultimate tensile strength increased for the 100% recycled sample compared to the virgin sample. The elongation at break decreased as the amount of recycled material increased. The mechanical properties of the PP blends can be viewed in Table 9.

*Multiple extrusion cycles*

In previous sections, the material underwent one recycling step. The current section assesses the influence of multiple recycling rounds on the young's modulus, ultimate tensile strength, and elongation at break. The material extruded multiple times included PET, PET-glycol (PETG) and PP.

Spinance et al. (2001) characterized the mechanical properties of PET as seen in Table 10. The properties were evaluated as a function of five processing cycles to which the material was yielded. The tensile strength was hardly affected, while the elongation at break was strongly affected as the number of processing cycles increased. The reduction of the elongation at break decreased drastically after three recycling rounds.

Van Kets et al. (2019) investigated the young's modulus, ultimate tensile strength, and elongation at the break of PET and PE after five extrusion cycles. After one recycling cycle, the young's modulus of PET increased significantly. The highest young's modulus value of PET was reached after four recycling cycles. The ultimate tensile strength remained equal, while the elongation at break decreased as the recycling rounds increased. The young's modulus and ultimate tensile strength of PP showed constant values over the five recycling cycles. During all recycling rounds, the elongation at break exceeded 300%. Table 10 provides the mechanical properties of PET and PE (Van Kets et al., 2019).

Vidakis et al. (2021) evaluated the mechanical properties of PETG after six recycling rounds. Table 10 shows that the highest young's modulus and ultimate tensile strength were achieved after the fourth recycling round.

La Mantia et al. (2021) studied the effect of five reprocessing cycles on the mechanical properties of a PP sample and a 70/30 PP blend consisting of 30% recycled material. Both samples obtained their optimal properties at zero recycling cycles. The young's modulus, ultimate tensile strength, and elongation at break decreased throughout the extrusion cycles. Figure 4 represents the mechanical properties of the virgin and reprocessed PP sample, where A represents the virgin sample, and A1, A2, and Ai after 1,2, and i extrusions. Figure 5 illustrates the mechanical properties of the 70/30 PP blend, where A represents the virgin sample, and R1, R2 and Ri after reprocessing the 70/30 PP blend 1,2, and i times. The young's modulus of the 70/30 PP blend was lower than the PP sample after five extrusion cycles. On the contrary, the 70/30 PP blend contained a higher ultimate tensile strength and elongation at break after five cycles. The values corresponding to Figure 4 and Figure 5 can be viewed in Table 10.

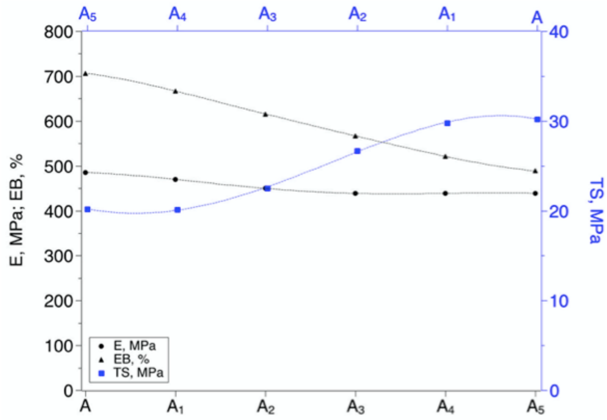


Figure 4. Elastic modulus (E), elongation at break (EB), and tensile strength (TS) of the virgin and reprocessed PP sample (La Mantia et al., 2021)

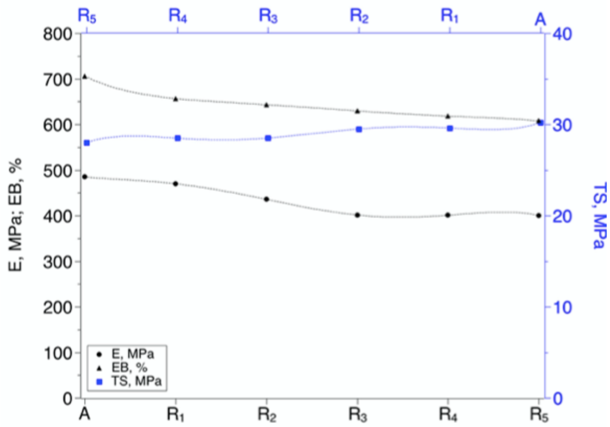


Figure 5. Elastic modulus (E), elongation at break (EB), and tensile strength (TS) of reprocessed 70/30 PP blend (La Mantia et al., 2021)

## Heterogeneous products

The previously described studies focused on the blend of one material. In this section, the blend of two or more materials is analyzed.

*Heteropolymer blends compared to their constituents*

Guerrero et al. (2001) investigated the effect of blending 75% PET with 25% HDPE. Blending the two components led to a drastic reduction of the elongation at break, as seen in Table 11. On the contrary, the values of the young's modulus and tensile strength fell between those of the pure constituents.

Kukaleva et al. (2003) evaluated the mechanical properties of recycled HDPE (r-HDPE), PP, LDPE, and a blend of these constituents. PP possessed the highest young's modulus and tensile strength at yield, whereas r-HDPE retained the highest elongation at break. Mixing r-HDPE with 23% PP increased the young's modulus and elongation at break. Adding 5% LDPE to the r-HDPE/PP blend decreased the young's modulus while the tensile strength at yield remained constant. Table 11 encapsulates the mechanical properties of the blends and its constituents (Kukaleva et al., 2003).

Nomura et al. (2020) studied the young's modulus, tensile strength at break, and elongation at break for PET, LDPE, and a 80/20 PET/LDPE blend. Table 11 summarizes the mechanical properties of the blend and its constituents. The young's modulus, tensile strength at break, and elongation at break of PET were higher compared to LDPE. Mixing PET with 20% LDPE resulted in lower mechanical properties, specifically the elongation at break (Nomura et al., 2020).

*Blends with an increased ratio of material*

Nir et al. (1995) studied the young's modulus, tensile strength at yield, and elongation at break when nylon6 was added to LDPE. As the content of nylon6 increased, the young's modulus, and tensile strength at yield increased. The elongation at break decreased (Nir et al., 1995).

Uehara et al. (2015) researched the tensile strength at yield, and the elongation at yield and break when PET was added to PE. Adding PET increased the tensile strength at yield while the elongation at yield decreased (Uehara et al., 2015).

Table 12 summarizes the results of the LDPE/nylon6 and PE/PET blends from Nir et al. (1995) and Uehara et al. (2015).

*Multiple extrusion cycles*

La Mantia and Capizzi et al. (2001) recycled a nylon6/PP blend by four repetitive extrusions. The tensile strength remained constant over the repeated extrusion steps. On the contrary, the elongation at break improved significantly over the processing cycles. In Table 13 the mechanical properties of the nylon6/PP blend can be viewed.

Van Kets et al. (2019) evaluated the effect of multiple extrusions on a heteropolymer blend without adding compatibilizers. Figure 6-8 represents the effect of five extrusions on respectively the young's modulus, tensile strength, and elongation at the break of PP (black bullet), PET (empty bullet), and a 75/25 PP/PET blend (black triangle down). The elongation at break of PP is outside the range of Figure 8 and is therefore not displayed. The empty triangle line includes a compatibilizer excluded in the current review. Table 10 summarizes the mechanical properties of PP and PET individually, while Table 13 represents the mechanical properties of the PP/PET blend. The young's modulus and tensile strength were not remarkably affected by multiple extrusions. A significant decrease was examined from the first to the third recycling cycle, followed by a further decrease from the third to fifth recycling cycle.

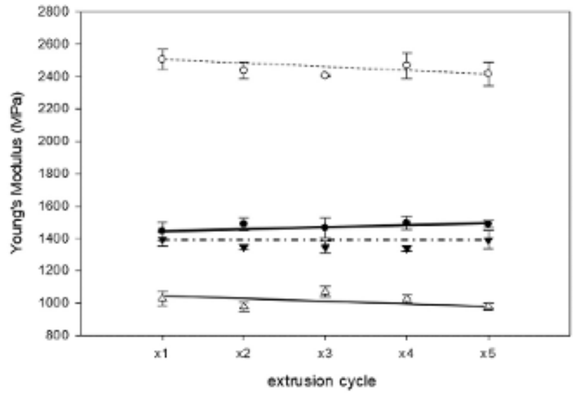


Figure 6. Young's modulus for PP (black bullet), PET (empty bullet), PP-PET (black triangle down), and PP-PET-SEBsgMAH (empty triangle up) after five extrusions cycles (Van Kets et al., 2019)

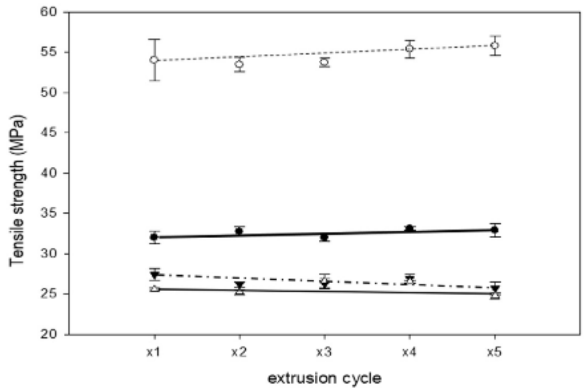


Figure 7. Tensile strength for PP (black bullet), PET (empty bullet), PP-PET (black triangle down), and PP-PET-SEBsgMAH (empty triangle up) after five extrusions cycles (Van Kets et al., 2019)

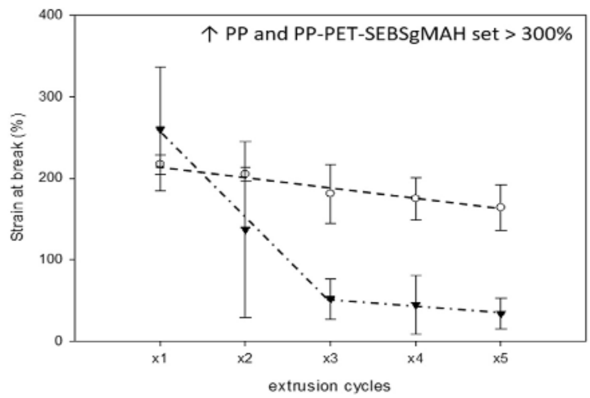


Figure 8. Strain at break for, PET (empty bullet) and PP-PET (black triangle down) after five extrusions cycles. PP and PP-PET-SEBsgMAH are outside the range (Van Kets et al., 2019)

## DISCUSSION

This systematic review presents an overview of the influence of recycling on the mechanical properties of plastics. The findings will be highlighted below, followed by the study's limitations and conclusion.

### General interpretation

Recycled PVC showed high elongation at break values and ductile behavior due to modifier agents in recycled material. Substantial degradation occured when no heat stabilizers were added to PVC before processing (Ma & LaMantia, 1996).

Recycled HDPE turned out to have superior mechanical properties compared to virgin HDPE. This observation could be due to the difference in the molecular weight of both materials. Recycled HDPE was contaminated with small amounts of PP, causing a higher young's modulus and tensile strength at yield, which could be seen as an advantage (Kukaleva et al., 2003).

The tensile strength of recycled LDPE was expected to increase due to crosslinking (Czarnecka-Komorowska et al., 2018; Mendes et al., 2011). In Kaiser and Ginzinger (2021), recycled LDPE was subjected to inconsiderable crosslinking. Accordingly, no increase was observed. The weakening of intermolecular interactions reduced the stiffness and increased the flexibility leading to an increased elongation at break (Fishman et al., 2000; Jantrawut et al., 2017; Muscat et al., 2012).

Although adding fillers or modifiers is an easy technique to improve the properties of recycled material, several studies, including a modifier, show extreme decreases in properties (Bahlouli et al., 2012). An alternative is to blend the recycled polymer with the same virgin material to ensure the properties (la Mantia et al., 2021; Scaffaro & La Mantia, 2002; Stoian et al., 2019). This method is also interesting from an environmental and economic viewpoint (Stoian et al., 2019). Homogeneous blends were expected to show roughly additive behavior with properties that fell between the two materials (Ma & LaMantia, 1996; Scaffaro & La Mantia, 2002). However, due to reprocessing, characteristics remained difficult to predict due to differences in crystallinity, molecular weight, and new functional groups present in the recycled material. Generally, the properties were depended on the recycled material (Scaffaro & La Mantia, 2002; La Mantia; Scheirs, 1998).

The scattering of the elongation at break for PVC blends in Ma and La Mantia (1996) could be caused by the inconsistent feeding of the extruder and insufficient dry blending. A different density for the virgin and recycled material was found. Therefore, the material that fell from the hopper into the extruder was not kept at a constant composition ratio. The incompatibility arose due to the different compositions. Besides the elongation at break, all blend compositions showed additive behavior.

The young's modulus and tensile strength were expected to decrease due to the different compositions in the recycled nylon6 blends (Scaffaro & La Mantia, 2002). The increase found, however, can be ascribed to the increase in crystallinity. Nylon6 crystallized during cooling. Therefore, only the crystalline component dictated the mechanical properties and distinct behavior in solid and molten states. As the number of recycled components in the blend increased, the crystallinity increased and became higher than the two constituents. The variation in elongation of break could be attributed to the decrease in molecular weight and increase in crystallinity which lowered the property. The blend containing 100% recycled material resulted in a more brittle and rigid material.

In Stoian et al. (2019), recycled PP possessed poorer mechanical properties due to thermomechanical degradation caused by multiple heat-shearing cycles. Virgin PP had a higher stiffness and strength. As the content of recycled material increased, the young's modulus and tensile strength decreased. Usually, a decrease in elongation at break would be expected, the inhomogeneity of the blend may have caused the the increase found in Stoian et al. (2019).

In Dobránsky et al. (2021), the values for the PP blend with increasing recycled content PP agreed with Samat et al. (2013) regarding the tensile strength. The results for the tensile strength at yield were confirmed by Yan et al. (2018), and Kada et al. (2018) and the results for the elongation before and after fraction were confirmed by Rizvi et al. (2017) and Reixach et al. (2015).

In contrast to Dobranksy et al. (2021) and Stoian et al. (2013), Van Straten et al. (2021) demonstrated that the ultimate tensile strength and young's modulus increased as the amount of recycled PP in the blend increased, while a lower elongation at break was found. The higher stiffness could be regarded as an advantage, depending on the application of the new injection-molded product (Van Straten et al, 2021). Van Straten et al. (2021) showed it was feasible to recycle PP waste and make new qualitative medical products without adding additives. The results show that when investigating the mechanical properties, it is preferable to use products that have the same application as the product under consideration.

Consequently, the mechanical properties of homogeneous material were researched after multiple extrusion cycles. An extruder transfered heat energy to the polymer through barrel sections, causing it to plasticize. The material was fed into the process by a spinning screw that guided it through barrel sections with varying temperatures. Finally, a nozzle was used to deliver molten plastic. Extrusion causes crosslinking, chain branching, and chain scission due to the heat stress and viscous shearing given to the polymer (Dynisco, 2021; Deng et al, 2014). The smaller molecular weight was the best indicator for chain scission (Van Kets et al., 2019). In the included studies, significant degradation did not occur during extrusion of the mono materials because the residence time was too short. According to literature, this is a common tendency for homogeneous materials (Badia et al., 2012).

Sinance et al. (2001) discovered changes in the mechanical properties of PET after three processing cycles.

Thermomechanical degradation decreases the molecular weight resulting in higher crystallinity (La Mantia & Vinci, 1994). The variations in molecular weight distribution and crystallization behavior in Sinance et al. (2001) contributed to the reduced properties.

The young's modulus and tensile strength researched in Van Kets et al. (2019) were much higher for PET than PP, which was as expected, but were not significantly influenced in both cases. Remarkable was the elongation at break in PP and PET. This value depended on intermolecular interactions and the tie chain molecules (Kim & Michler, 1998). Through all extrusion cycles, PP had an elongation above 300%, due to disentanglements of the polymer chains. Regarding PET, the elongation at break occurred above 150%, which was unpredicted and was attributed to the oscillatory deformation mechanism. The alternating shear yielding caused oscillations in the stress-strain curve. The constant decrease was due to the degradation of the material, which could no longer endure the same level of deformation after five extrusions.

PETG, which had improved properties compared to PET, could be heat blended due to its low forming temperatures. Multiple recycling rounds improved the recycled material's mechanical stability, especially after the third and fourth rounds when specimens were stiffer. Thermomechanical processing could cause a strengthening mechanism during recycling but was overcome by inherent degradation as the recycling rounds continued. The brittle and ductile behavior found in Vidakis et al. (2021) may be caused by the amorphous structure of PETG, leading to polymeric chains being shortened or reoriented inside the material. While some studies show a slight increase in tensile strength (Zander, 2018), the decrease found in (Vidakis et al., 2021) is also in line with other studies (Cole et al., 1994; Ward & Wilding, 1977; Gharbi et al., 2000).

In La Mantia et al. (2021), the PP and 70/30 PP blend samples showed similar behavior. The decrease in tensile strength and elongation at break was due to a smaller molecular weight. In previous literature, it has been observed that semi-crystalline polymers can show an increase or decrease in young's modulus attributed to two different mechanisms. A reduction in molecular weight can cause a decrease in young's modulus. An increase can be caused by an increase in crystallinity degree (Valenza & La Mantia, 1998). When the sample was reprocessed five times, the crystallinity degree was higher. As the recycled component in the blend degraded, the materials became incompatible, leading to a change in crystalline morphology. Crystallinity is related to thermal properties. However, thermal degradation was outside the scope of this study.

Accordingly, the results for heterogeneous products will be discussed. Blending two different polymers could lead to incompatible blends with properties that could not be forecasted based on the mechanical properties of the separate constituents. Usually, these were lower than expected based on the additive rule. The 75/25 PET/HDPE blend observed by Guerrero et al. (2021) became very fragile compared to its constituents. Similarly, the PET/LDPE blend in Nomura et al. (2020) became very brittle, in contrast to the neat form where PET could be extended by 200% and PE by 800%. The poor interfacial adhesion between the two phases in the blend led to immiscible materials and poor properties of the uncompatibilized blend. The addition of compatibilizers could significantly influence the mechanical properties. However, compatibilizers were outside the scope of the current study.

Kukaleva et al. (2003) researched the mechanical properties of an HDPE and HDPE/LDPE blend with the addition of PP as a modifying component. PP was known for its low viscosity and high shear-thinning behavior, making it an excellent material for injection molding. HDPE had a high viscosity. Hence, a blend with HDPE would lower the viscosity considerably, allow easier processing, and was expected to show additive behavior regarding the young's modulus and tensile strength (Kukaleva et al., 2003). PP was known to embrittle PE but also increase melt flowability. Adding 23% PP to r-HDPE led to a more elastic and robust material. HDPE and LDPE were miscible in a solid and molten state; therefore, blends had remarkable mechanical properties. Adding 5% PP to the r-HDPE/LDPE blends led to a minor decrease in mechanical properties while the melt flowability increased. Adding PP to HDPE and HDPE/LDPE would show compatible behavior when crystallization coincides.

The degree of crystallinity affected the mechanical properties of the LDPE/nylon6 and PET/PE blends. The components in the blends crystallized at different times. In both cases, compatibilization would enhance the properties of the blend. Increasing the content of nylon6 to LDPE led to the material losing its stiffness and toughness (Nir et al., 1995). Uehara et al. (2015) found that increasing the amount of PET to PE led to a higher tensile strength at yield and lower elongation at break at yield, attributed to PET being a more rigid material.

Finally, the effect of multiple extrusions on the binary 80/20 nylon6/PP and 75/25 PP/PET blend is discussed. The mechanical properties of blends strongly depended on their composition. The increasing elongation at break values reported by La Mantia and Capizzi (2001) could be explained by the refined adhesion between nylon6 and PP. The properties of the recycled blend were slightly improved due to the formation of new bridges between the two polymers. Of course, as the number of extrusion steps increased, some degradation could be attributed to the lower molecular weight (La Mantia & Capizzi, 2001). In Kets et al. (2019), the 75/25 PP/PET blend showed similar behavior to PP as the blend comprised of 75% PP. The properties did not change over multiple extrusion cycles since the composition over the cycles did not alter. PET could not increase the tensile strength because the interfacial adhesion of the two components was low. Accordingly, the low-stress transfer resulted in a rapid decrease of the elongation at break. Degradation occured due to destabilization and a decrease in molecular weight (Van Kets et al., 2019).

### Limitations

The findings of this systematic review should be considered with some limitations, which will be discussed below.

In this review, articles were included in the study when they focused on the materials found in the first literature research. The final search found articles on PP, PE, PVC, PET, and nylon 6. The articles which focused on PS and PC did not meet the inclusion criteria as the blend contained compatibilizers or were mixed with material outside the scope of the study. Therefore, it is seen as a limitation that not all materials found in the first literature research were included in the second systematic review.

Compatibilizers were excluded in this review as they influence the interaction between polymers, affect the degradation mechanisms, and harm recycling. Simultaneous crystallization is an alternative to the compatibilization of immiscible blends. This concept is considered when the crystallization temperatures overlap (Nadkami & Jog, 1991). Therefore, the melting behavior and crystallinity are significant features related to materials' mechanical properties and processability (Stoian et al., 2019). Similarly, the mechanical properties are related to the processing parameters. Several processing parameters, such as screw rotational speed and extrusion temperatures, are controllable and must be optimized since they influence the degradation (Vidakis et al., 2021). It is seen as a limitation that these parameters were not considered in the current study. Unfortunately, it was beyond the scope of this literature review to research the influence of thermal and processing parameters on mechanical properties.

Another limitation of the research is that the search is carried out in two databases. The rule of thumb for systematic literature research is to use more than two databases (Charrois, 2015). As a result, the lack of an additional database is a limitation, as this would have allowed for a more comprehensive overview of the mechanical properties. Due to time constraints, the search was not conducted in an additional database.

Finally, a complete search is needed to identify the literature thoroughly. One reviewer performed this literature study, whereas a systematic review is advised to be conducted by at least two independent reviewers to reduce the chance of bias. The help of a librarian who has expertise in defining search terms, search strategies, and databases would be an excellent approach to ensure the most extensive scope of studies is identified (Charrois, 2015). Considering that one reviewer performed the selection of articles, this could be regarded as a limitation as relevant articles might be excluded.

### Conclusion

The objective of this systematic review was to study the influence of recycling on the mechanical properties of plastics. A higher young's modulus and tensile strength appear to be related to a higher crystallinity and lower elongation at break with decreasing molecular weight. Polymer blending is an intriguing technique for creating new polymeric materials with tailored properties. Homogeneous blends remain miscible if the degradation of the recycled material has not changed the chemical structure of the recycled polymer. The immiscibility of polymers affects the properties of heterogeneous blends more when blended. Blends must be considered biphasic materials, with inhomogeneities causing a variation in the mechanical properties. The mechanical properties of blends changed as a result of the processing steps. Property degradation is minimal, and some improvement can be seen after three or four extrusion steps. The current review found articles related to homogeneous and heterogeneous blends. Mechanical properties were compared between virgin and recycled components, blends and their constituents, blends with increasing ratio content of recycled material, and properties after multiple extrusion cycles. Future work should focus on only one category to perform more in-depth research.

## GENERAL DISCUSSION: RECYCLING MEDICAL PLASTIC PACKAGES

Combining the results of the first and second systematic reviews provides information on the recyclability of medical plastic packages. A general interpretation of the findings will be outlined below, followed by a limitation and conclusion of the study.

### General interpretation

The operating room (OR) has a high recycling potential for medical plastics, and medical packaging would be one of the first products considered to be recycled (Gill et al., 2020). The prevailing solution for mechanical recycling is sorting the material according to polymer type (Lee et al., 2002). Material properties can be affected by blending them with the same virgin polymer, blending them with a different polymer, or extruding the material multiple times.

### Limitation

The findings of the first and second systematic review should be considered with a limitation. The first systematic review provided information on the materials found in medical plastic packaging and the second systematic review researched the influence of recycling on the mechanical properties of plastics. The choice was made to perform two separate research due to the scarcity of published data on mechanical recycling of medical plastics. Since the material investigated in the second study was derived from various uses rather than medical packaging, this could be considered a limitation.

### Conclusion

The aim of this literature review was to map the research conducted on the recyclability of medical plastic packaging, identify existing literature gaps, and make recommendations for future research. To conclude, the first deliberation for hospital waste management should be recycling processes to move towards a circular economy. Incineration should only be considered for non-recyclable products as this process affects the environment due to releasing toxic gases. Medical packages which include one polymer can be recycled in neat form. Recycling multilayer packaging is more challenging than monopolymer packaging due to the different components.

Modified RMW guidelines, proper source segregation, and moving towards monomaterials in medical packaging would alleviate the recyclability. Mechanical properties differ per application; therefore, it is essential to research the effect of recycling on medical plastic packages. Follow-up studies should explore additional polymers from hospital waste during recycling to gain more knowledge on the recyclability of medical plastic packages.

## Reference list


Badia, J., Strömberg, E., Karlsson, S., & Ribes-Greus, A. (2012). The role of crystalline, mobile amorphous and rigid amorphous fractions in the performance of recycled poly (ethylene terephthalate) (PET). *Polymer Degradation and Stability*, *97*(1), 98–107. https://doi.org/10.1016/j.polymdegradstab.2011.10.008

Bahlouli N, Pessey D, Raveyre C, Guillet J, Ahzi S, Dahoun A, Hiver JM. Recycling effects on the rheological and thermome- chanical properties of polypropylene-based composites. Mater Des. 2012;33:451–8.

Brookman, R. S. (1991). New PVC based polymer for medical applications. 49th Annual Technical Conference -ANTEC '91, Brookfield, CT, United States Montreal, Que, Can.

Cabrera, G., Touil, I., Masghouni, E., Maazouz, A., & Lamnawar, K. (2021). Multi-micro/nanolayer films based on polyolefins: New approaches from eco-design to recycling [Article]. *Polymers, 13*(3), 1-21, Article 413. https://doi.org/10.3390/polym13030413

Charrois T. L. (2015). Systematic reviews: what do you need to know to get started?. *The Canadian journal of hospital pharmacy*, *68*(2), 144–148. https://doi.org/10.4212/cjhp.v68i2.1440

Chen, H. Q., Jiang, B. H., & Cai, Z. Q. (2015, Sep). Preparation and properties of paper-plastic laminating adhesive used for medical packaging materials [Article]. *Polymers for Advanced Technologies, 26*(9), 1065-1069. https://doi.org/10.1002/pat.3533

Chen, X. Z., Kroell, N., Feil, A., & Pretz, T. (2020, Dec). DETERMINATION OF THE COMPOSITION OF MULTILAYER PLASTIC PACKAGING WITH NIR SPECTROSCOPY [Article]. *Detritus, 13*, 62-66. https://doi.org/10.31025/2611-4135/2020.14027

Cole, K.C.; Guevremont, J.; Ajji, A.; Dumoulin, M.M. Characterization of surface orientation in poly(ethylene terephthalate) by front-surface reflection infrared spectroscopy. *Appl. Spectrosc.* **1994**, *48*, 1513–1521.

Costa, L., Bracco, P., Brach Del Prever, E. M., Kurtz, S. M., & Gallinaro, P. (2006). Oxidation and oxidation potential in contemporary packaging for polyethylene total joint replacement components [Article]. *Journal of Biomedical Materials Research - Part B Applied Biomaterials, 78*(1), 20-26. https://doi.org/10.1002/jbm.b.30454

Czerniawski, B. (1990). Flexible packaging of disposable medical devices—A review [Article]. *Packaging Technology and Science, 3*(4), 203-217. https://doi.org/10.1002/pts.2770030405

Demertzis, P.G.; Franz, R.; Welle, F. (1999) The effects of ɤ -irradiation on compositional changes in plastic packaging films. Packaging Technology and Science, v.12, p.119-130.

Deng, J.; Li, K.; Harkin-Jones, E.; Price, M.; Karnachi, N.; Kelly, A.; Vera-Sorroche, J.; Coates, P.; Brown, E.; Fei, M. Energy monitoring and quality control of a single screw extruder. *Appl. Energy* **2014**, *113*, 1775–1785.

Dharmaraj, S., Ashokkumar, V., Pandiyan, R., Halimatul Munawaroh, H. S., Chew, K. W., Chen, W. H., & Ngamcharussrivichai, C. (2021). Pyrolysis: An effective technique for degradation of COVID-19 medical wastes [Review]. *Chemosphere, 275*, Article 130092. https://doi.org/10.1016/j.chemosphere.2021.130092

Dixon, D., McIlhagger, A. T., Crangle, A. A., McIlhagger, R., & McCracken, K. (2007). Seal properties of medical packaging materials at elevated temperature [Article]. *Journal of Adhesion Science and Technology, 21*(15), 1529-1537. https://doi.org/10.1163/156856107782844774

Dobránsky, J., Pollák, M., Běhálek, L., & Svetlík, J. (2021). Implementation of a recycled polypropylene homopolymer material for use in additive manufacturing [Article]. *Sustainability (Switzerland), 13*(9), Article 4990. https://doi.org/10.3390/su13094990

ĐUzelić, R., & Hadžalić, M. (2018). Effects and Optimization of Process Parameters on Seal Integrity for Terminally Sterilized Medical Devices Packaging. *Advanced Technologies, Systems, and Applications III*, 355–365. https://doi.org/10.1007/978-3-030-02577-9_35

Dynisco. Introduction to Extrusion. 2021. Available online: https://www.dynisco.com/knowledge-center/index.cfm?tid= Handbooks-17 (accessed on 18 January 2021).

Fishman, M.L.; Coffin, D.R.; Konstance, R.P.; Onwulata, C.I. Extrusion of pectin/starch blends plasticized with glycerol. *Carbohydr. Polym.* **2000**, *41*, 317–325.

Fletcher, C. A., St Clair, R., & Sharmina, M. (2021, JUL 15). A framework for assessing the circularity and technological maturity of plastic waste management strategies in hospitals. *JOURNAL OF CLEANER PRODUCTION, 306*. https://doi.org/10.1016/j.jclepro.2021.127169

Gahleitner, M., Wolfschwenger, J., Fiebig, J., Dobianer, K., & Hametner, C. (2003). Sterilization effects on polypropylene: Technology and polymer type effects. Proceedings of the 2003 TAPPI European PLACE Conference, Rome.

Gharbi, S.; Andreolety, J.P.; Gandini, A. Polyesters bearing furan moieties IV. Solution and interfacial polycondensation of 2,2′-bis(5-chloroformyl-2-furyl)propane with various diols and bisphenols. *Eur. Polym. J.* **2000**, *36*, 463–472.

Gill, Y. Q., Khurshid, M., Abid, U., & Ijaz, M. W. (2022). Review of hospital plastic waste management strategies for Pakistan [Review]. *Environmental Science and Pollution Research,* *29*(7), 9408-9421. https://doi.org/10.1007/s11356-021-17731-9

Granholm, T., Creasy, D. M., Pöllänen, P., & Söder, O. (1992). Di-n-pentyl phthalate-induced inflammatory changes in the rat testis are accompanied by local production of a novel lymphocyte activating factor [Article]. *Journal of Reproductive Immunology, 21*(1), 1-14. https://doi.org/10.1016/0165-0378(92)90036-4

Grigore, M. (2017). Methods of Recycling, Properties and Applications of Recycled Thermoplastic Polymers. *Recycling*, *2*(4), 24. https://doi.org/10.3390/recycling2040024

Guerrero, C.; Lozano, T.; GonzaÍez, V.; Arroyo, E. Properties and Morphology of Poly(Ethylene Terephthalate) and High-Density Polyethylene Blends. J. Appl. Polym. Sci. 2001, 82 (6), 1382–1390.

Guyer, E., & Zednik, R. J. (2010). Sterile barriers for medical devices: Failure modes and mitigation. 68th Annual Technical Conference of the Society of Plastics Engineers 2010, ANTEC 2010, Orlando, FL.

Haned, Z., Moulay, S., & Lacorte, S. (2018, Jul). Migration of plasticizers from poly(vinyl chloride) and multilayer infusion bags using selective extraction and GC-MS [Article]. *Journal of Pharmaceutical and Biomedical Analysis, 156*, 80-87. https://doi.org/10.1016/j.jpba.2018.04.011

*Healthcare Plastic Waste*. (2021). Circulair Ondernemen. Geraadpleegd op 5 maart 2021, van https://www.circulairondernemen.nl/uploads/669c6eb7189f26e44986a9ef69c15569.pdf

Hong, K. Z. (1996). Poly(Vinyl Chloride) in Medical Device and Packaging Applications [Article]. *Journal of Vinyl and Additive Technology, 2*(3), 193-197. https://doi.org/10.1002/vnl.10123

Horodytska, O., Valdés, F. J., & Fullana, A. (2018). Plastic flexible films waste management – A state of art review [Review]. *Waste Management, 77*, 413-425. https://doi.org/10.1016/j.wasman.2018.04.023

Jang, Y. C., Lee, C., Yoon, O. S., & Kim, H. (2006). Medical waste management in Korea [Article]. *Journal of Environmental Management, 80*(2), 107-115. https://doi.org/10.1016/j.jenvman.2005.08.018

Jantrawut, P.; Chaiwarit, T.; Jantanasakulwong, K.; Brachais, C.H.; Chambin, O. Effect of Plasticizer Type on Tensile Property and In Vitro Indomethacin Release of Thin Films Based on Low-Methoxyl Pectin. *Polymers* **2017**, *9*, 289.

Kada, D.; Koubaa, A.; Tabak, G.; Migneault, S.; Garnier, B.; Boudenne, A. Tensile properties, thermal conductivity, and thermal stability of short carbon fiber reinforced polypropylene composites. *Polym. Compos.* **2018**, *39*, 664–670.

Kaiser, K. M. A., & Ginzinger, T. (2021). Production of a pet//ldpe laminate using a reversibly crosslinking packaging adhesive and recycling in a small-scale technical plant [Article]. *Recycling, 6*(3), Article 47. https://doi.org/10.3390/recycling6030047

Kim, G.M., Michler, G., Micromechanical deformation processes in toughened and particle filled semicrystalline polymers: Part 2. model representation for micromechanical deformation processes, Polymer 39 (23) (1998) 5699e5703.

Kukaleva, N., Simon, G. P., & Kosior, E. (2003). Binary and Ternary Blends of Recycled High-Density Polyethylene Containing Polypropylenes [Article]. *Polymer Engineering and Science, 43*(2), 431-443. https://doi.org/10.1002/pen.10035

Kumar, K. T., Raghu, S., & Shanmugharaj, A. M. (2022, MAR 17). Transmogrifying waste blister packs into defect-engineered graphene-like turbostratic carbon: novel lithium-ion (Li-ion) battery anode with noteworthy electrochemical characteristics. *NANOSCALE, 14*(11), 4312-4323. https://doi.org/10.1039/d1nr07183a

Kwon, H., Kim, D., Lee, K. D., Seo, J., & Lee, H. J. (2017, May). The Effect of Coating Process and Additives on EVA Coated Tyvek (R) for Gas Sterilizable Medical Packaging Applications [Article]. *Packaging Technology and Science, 30*(5), 195-208. https://doi.org/10.1002/pts.2293

La Mantia, F. P. (1992). Recycling of heterogeneous plastics wastes: I-Blends with low-density polyethylene [Article]. *Polymer Degradation and Stability, 37*(2), 145-148. https://doi.org/10.1016/0141-3910(92)90077-I

La Mantia, F.P. (1998), *Frontiers in the Science and Technology of Polymer Recycling*, p.385, G. Akovali, C.A. Bernardo, J. Leidner, L.A. Utracki, and M. Xanthos, eds.

la Mantia, F. P., Mistretta, M. C., & Titone, V. (2021). An additive model to predict the rheological and mechanical properties of polypropylene blends made by virgin and reprocessed components [Article]. *Recycling, 6*(1), 1-11, Article 2. https://doi.org/10.3390/recycling6010002

La Mantia, F., Capizzi, L. (2001) Recycling of compatibilized and uncompatibilized nylon/polypropylene blends, Polym. Degrad. Stabil. 71 (2) 285e291.

Lee, B. K., Ellenbecker, M. J., & Moure-Eraso, R. (2002). Analyses of the recycling potential of medical plastic wastes [Article]. *Waste Management, 22*(5), 461-470. https://doi.org/10.1016/S0956-053X(02)00006-5

Li, F. M., Wang, Y., Liu, X. G., & Yang, B. Y. (2000, Mar). Evaluation of plastic packaging materials used in radiation sterilized medical products and food [Article; Proceedings Paper]. *Radiation Physics and Chemistry, 57*(3-6), 435-439. <Go to ISI>://WOS:000086653700052

Luqueta, G. R., Dos Santos, E. D., Pessoa, R. S., & Maciel, H. S. (2017). Evaluation of disposable medical device packaging materials under ozone sterilization [Article]. *Revista Brasileira de Engenharia Biomedica, 33*(1), 58-68. https://doi.org/10.1590/2446-4740.03216

Ma, W. G., & LaMantia, F. P. (1996, JAN 31). Processing and mechanical properties of recycled PVC and of homopolymer blends with virgin PVC. *Journal of Applied Polymer Science, 59*(5), 759-767.

Mallegol, J., Carlsson, D. J., & Deschenes, L. (2001). Antioxidant effectiveness of vitamin E in HDPE and tetradecane at 32 degrees C [Article]. *Polymer Degradation and Stability, 73*(2), 269-280. https://doi.org/10.1016/s0141-3910(01)00087-8

Martin, N., Smith, L., & Mulligan, S. (2021). Sustainable oral healthcare and the environment: Mitigation strategies [Article]. *Dental Update, 48*(7), 524-531. https://doi.org/10.12968/DENU.2021.48.7.524

Massey, L. K. (2005). *The Effect of Sterilization Methods on Plastics and Elastomers, 2nd Edition* [Book]. William Andrew. https://www.scopus.com/inward/record.uri?eid=2-s2.084881719279&partnerID=40&md5=f25706ed48543abed7dc76e737f8024d

McKeen, L. W. (2017). *Film Properties of Plastics and Elastomers: Fourth Edition* [Book]. Elsevier.

Mendes, A.A.; Cunha, A.M.; Bernardo, C.A. Study of the degradation mechanisms of polyethylene during reprocessing. *Polym. Degrad. Stab.* **2011**, *96*, 1125–1133.

Mulakkal, M. C., Castillo Castillo, A., Taylor, A. C., Blackman, B. R. K., Balint, D. S., Pimenta, S., & Charalambides, M. N. (2021). Advancing mechanical recycling of multilayer plastics through finite element modelling and environmental policy [Article]. *Resources, Conservation and Recycling, 166*, Article 105371. https://doi.org/10.1016/j.resconrec.2020.105371

Muscat, D.; Adhikari, B.; Adhikari, R.; Chaudhary, D.S. Comparative study of film forming behaviour of low and high amylose starches using glycerol and xylitol as plasticizers. *J. Food Eng.* **2012**, *109*, 189–201.

Nadkami, V.M., & Jog, J.P. "Crystallization Behavior in Polymer Blends," in **Two-Phase Polymer Systems,** edited by L. A. Utracki, Hanser Publishers, Munich, Vi- enna, New York, Barcelona **(1991).**

Nase, M., Bach, S., Zankel, A., Majschak, J. P., & Grellmann, W. (2013, Oct). Ultrasonic sealing versus heat conductive sealing of polyethylene/polybutene-1 peel films [Article]. *Journal of Applied Polymer Science, 130*(1), 383-393. https://doi.org/10.1002/app.39171

Nir, M. M., Ram, A., & Miltz, J. (1995). Performance of reprocessed multilayer LDPE/nylon-6 film [Article]. *Polymer Engineering & Science, 35*(23), 1878-1883. https://doi.org/10.1002/pen.760352307

Nomura, K., Peng, X. Y., Kim, H., Jin, K. L., Kim, H. J., Bratton, A. F., Bond, C. R., Broman, A. E., Miller, K. M., & Ellison, C. J. (2020, FEB 26). Multiblock Copolymers for Recycling Polyethylene-Poly(ethylene terephthalate) Mixed Waste. *ACS APPLIED MATERIALS & INTERFACES, 12*(8), 9726-9735. https://doi.org/10.1021/acsami.9b20242

North, E. J., & Halden, R. U. (2013). Plastics and environmental health: The road ahead [Review]. *Reviews on Environmental Health, 28*(1), 1-8. https://doi.org/10.1515/reveh-2012-0030

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., . . . Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*, n71. https://doi.org/10.1136/bmj.n71

Portnoy, R. C. (1997). Plastomer modified polypropylene films for medical product packaging. Proceedings of the 1997 55th Annual Technical Conference, ANTEC. Part 3 (of 3), Brookfield, CT, United States Toronto, Can.

Pinjing, H., Fan, L., Hua, Z., Liming, S., 2013. Reference to the circular economy as a guiding principle. Waste as a Resource 37, 144.

Porto, K., Napolitano, C. M., & Borrely, S. I. (2018, Jan). Gamma radiation effects in packaging for sterilization of health products and their constituents paper and plastic film [Article]. *Radiation Physics and Chemistry, 142*, 23-28. https://doi.org/10.1016/j.radphyschem.2016.12.019

Puangsa-Ard, Y., Thaweboon, S., Jantaratnotai, N., & Pachimsawat, P. (2018). Effects of resterilization and storage time on sterility of paper/plastic pouches [Article]. *European Journal of Dentistry, 12*(3), 417-421. https://doi.org/10.4103/ejd.ejd_351_17

Reixach, R.; Espinach, F.X.; Arbat, G.; Julian, F.; Delgado-Aguilar, M.; Puig, J.; Mutje, P. Tensile properties of polypropylene composites reinforced with mechanical, thermomechanical, and chemi-thermomechanical pulps from orange pruning. *Bioresources* **2015**, *10*, 4544–4556.

Rizvi, S.J.A.; Singh, A.K.; Bhadu, G.R. Optimization of tensile properties of injection molded alpha-nucleated polypropylene using response surface methodology. *Polym. Test.* **2017**, *60*, 198–210.

Rosato, D. V. (2011). Plastics End Use Application Fundamentals. *Plastics End Use Applications*, 11–18. https://doi.org/10.1007/978-1-4614-0245-9_2

Samat, N.; Marini, C.D.; Maritho, M.A.; Sabaruddin, F.A. Tensile and impact properties of polypropylene/microcrystalline cellulose treated with different coupling agents. *Compos. Interfaces* **2013**,*20*, 497–506.

Scaffaro, R., & La Mantia, F. P. (2002). Characterization of monopolymer blend of virgin and recycled polyamide 6 [Article]. *Polymer Engineering and Science, 42*(12), 2412-2417. https://doi.org/10.1002/pen.11127

Scheirs, J., *Polymer Recycling*, John Wiley & Sons, United States (1998)

Selcuk, A. A. (2019). A Guide for Systematic Reviews: PRISMA. *Turkish Archives of Otorhinolaryngology*, *57*(1), 57–58. https://doi.org/10.5152/tao.2019.4058

Shinn, H. K., Hwang, Y., Kim, B. G., Yang, C., Na, W., Song, J. H., & Lim, H. K. (2017, Feb). Segregation for reduction of regulated medical waste in the operating room -a case report [Article]. *Korean Journal of Anesthesiology, 70*(1), 100-104. https://doi.org/10.4097/kjae.2017.70.1.100

Spinace, M.S., De Paoli, M., (2001) Characterization of poly (ethylene terephtalate) after multiple processing cycles, J. Appl. Polym. Sci. 80 (1) 20e25.

Starr, L. D. (1986). Productivity Gains in High Barrier Medical Packaging [Article]. *Journal of Plastic Film & Sheeting, 2*(1), 63-74. https://doi.org/10.1177/875608798600200107

Stoian, S. A., Gabor, A. R., Albu, A. M., Nicolae, C. A., Raditoiu, V., & Panaitescu, D. M. (2019). Recycled polypropylene with improved thermal stability and melt processability [Article]. *Journal of Thermal Analysis and Calorimetry, 138*(4), 2469-2480. https://doi.org/10.1007/s10973-019-08824-2

Technische Universiteit Delft. (2021, 4 november). *Making a search plan »*. TUlib. Geraadpleegd op 24 mei 2022, van https://tulib.tudelft.nl/searching-resources/making-a-search-plan/

Uehara, G. A., Franca, M. P., & Canevarolo, S. V. (2015, JUL-AUG). Recycling assessment of multilayer flexible packaging films using design of experiments. *POLIMEROS-CIENCIA E TECNOLOGIA, 25*(4), 371-381. https://doi.org/10.1590/0104-1428.1965

Valenza, A.; La Mantia, F.P. Recycle of polymer waste: Part 2 Stress degraded polypropylene. *Polym. Deg. Stab.* **1998**, *20*, 63.

Van Kets, K., Delva, L., & Ragaert, K. (2019). Structural stabilizing effect of SEBSgMAH on a PP-PET blend for multiple mechanical recycling [Article]. *Polymer Degradation and Stability, 166*, 60-72. https://doi.org/10.1016/j.polymdegradstab.2019.05.012

Van Straten, B., Dankelman, J., Van der Eijk, A., Horeman, T., 2020. A Circular Healthcare Economy; a feasibility study to reduce surgical stainless steel waste. Sustainable Production and Consumption 27, 169–175.

Van Straten, B., Van der Heiden, D., Robertson, D., Riekwel, C., Jansen, F., Van der Elst, M., & Horeman, T. (2021). Surgical waste reprocessing: Injection molding using recycled blue wrapping paper from the operating room. *Journal of Cleaner Production*, *322*, 129121. https://doi.org/10.1016/j.jclepro.2021.129121

Vidakis, N., Petousis, M., Tzounis, L., Grammatikos, S. A., Porfyrakis, E., Maniadi, A., & Mountakis, N. (2021). Sustainable additive manufacturing: Mechanical response of polyethylene terephthalate glycol over multiple recycling processes [Article]. *Materials, 14*(5), 1-16, Article 1162. https://doi.org/10.3390/ma14051162

Ward, I.M.; Wilding, M.A. Infra-red and Raman spectra of poly(m-methylene terephthalate) polymers. *Polymer* **1977**, *18*, 327–335.

Woo, L., & Ling, M. T. K. (1992). Cryogenic impact properties of medical packaging films [Article]. *Journal of Plastic Film & Sheeting, 8*(1), 11-25. https://doi.org/10.1177/875608799200800103

Woo, L., & Sandford, C. L. (2002). Comparison of electron beam irradiation with gamma processing for medical packaging materials [Article]. *Radiation Physics and Chemistry, 63*(3-6), 845-850. https://doi.org/10.1016/S0969-806X(01)00664-8

Yan, X.F.; Yang, Y.Q.; Hamada, H. Tensile properties of glass fiber reinforced polypropylene composite and its carbon fiber hybrid composite fabricated by direct fiber feeding injection molding process. *Polym. Compos.* **2018**, *39*, 3564–3574.

**APPENDIX**

**Table 1** Search string Scopus and Web of Science

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Scopus | TITLE-ABS-KEY ((*plastic* OR polymer) | **AND** | (packag*) | **W/25** | (hospital* OR clinical* OR *medical* OR "operating room*" OR surgical*) | **AND** | (material* OR composition*)) | **OR** | ((medical OR clinical OR hospital) | **W/15** | ("waste management" OR "waste stream" | **AND** | plastic |
| Web of Science | ((*plastic* OR polymer) | **AND** | (packag*) | **Near/25** | (hospital* OR clinical* OR *medical* OR "operating room*" OR surgical*) | **AND** | (material* OR composition*)) | **OR** | ((medical OR clinical OR hospital) | **Near/15** | ("waste management" OR "waste stream" | **AND** | plastic |

**Table 2** Polymer type in monopolymer medical packaging

| Authors, year | PP | PE | PET | PVC | PS | Nylon6 | PA |
|---|---|---|---|---|---|---|---|
| Czerniawski, 1990 | ■ | ■ | ■ | ■ | ■ | | |
| Brookman, 1991 | | | | ■ | | | |
| Granholm et al., 1992 | | | | ■ | | | |
| Woo & Ling, 1992 | | LDPE | | ■ | | | |
| Hong, 1996 | | | | ■ | | | |
| Portnoy, 1997 | ■ | | ■ | ■ | | | |
| Demertzis et al., 1999 | ■ | ■ | ■ | ■ | ■ | | ■ |
| Li et al., 2000 | ■ | ■ | | ■ | | ■ | |
| Mallegol et al., 2001 | | HDPE | | | | | |
| Lee et al., 2002 | | ■ | | ■ | ■ | | |
| Woo & Sandford, 2002 | ■ | ■ | | | | | |
| Gahleitner et al., 2003 | ■ | | | | | | |
| Massey, 2005 | ■ | | ■ | ■ | ■ | | |
| Costa et al., 2006 | | | ■ | | | | |
| Jang et al., 2006 | | | | ■ | | | |
| Rosato, 2011 | ■ | ■ | | ■ | ■ | ■ | |
| Nase et al., 2013 | | LDPE | | | | | |
| North & Halden, 2013 | ■ | | | | | | |
| Luqueta et al., 2017 | ■ | ■ | ■ | | | | |
| Shinn et al., 2017 | ■ | | | | | | |
| Haned et al., 2018 | | | | ■ | | | |
| Chen et al., 2020 | ■ | LDPE | ■ | | | | |
| Van Straten et al., 2020 | ■ | | | | | | |
| Dharmaraj et al., 2021 | ■ | ■ | ■ | | ■ | | |
| Fletcher et al., 2021 | ■ | ■ | | ■ | ■ | | |
| Martin et al., 2021 | ■ | ■ | | ■ | ■ | | |
| Gill et al., 2022 | ■ | HDPE | | ■ | | | |
| Kumar et al., 2022 | ■ | | ■ | ■ | ■ | | |

**Table 3** Polymer type in multilayered medical packaging

| Authors, year | PP/PE | PP/PET | PE/PET | PP/PET/PE | Nylon/EVOH/PE | CFTE/PVC |
|---|---|---|---|---|---|---|
| Starr, 1986 | | | | | ■ | ■ |
| Costa et al., 2006 | | | ■ | | | |
| Nase et al., 2013 | LDPE | | | | | |
| Chen et al., 2020 | LDPE | LDPE | LDPE | LDPE | | |

**Table 4** Polymer type in paper-plastic medical packaging

| Authors, year | Monopolymer | | | Multilayer | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | PP | PE | Polyester | PET/PP | PET/PE | Polyester/PP | Polyester/PE | PA/PE | PA/PP | Nylon/PVC/PE |
| Czerniawski, 1990 | | | | | | | | | | |
| Chen et al., 2015 | | | | | | | | | | |
| Luqueta et al., 2017 | | | | | | | | | | |
| McKeen, 2017 | | | | | | | | | | |
| Porto et al., 2018 | | | | | | | | | | |
| Puangsa-Ard et al., 2018 | | | | | | | | | | |
| Duzelić & Hadželić, 2019 | | | | | | | | | | |

**Table 5** Polymer type in Tyvek-plastic medical packaging

| Authors, year | Monopolymer | | | | Multilayer | | |
|---|---|---|---|---|---|---|---|
| | PP | PE | PET | PC | PET/PE | Polyester/PE | PE/Nylon |
| Dixon et al., 2007 | | | | | | | |
| Guyer & Zednik, 2010 | | HDPE | | | | | |
| Kwon et al., 2017 | | | | | | | |
| Luqueta et al., 2017 | | | | | | | |
| McKeen, 2017 | | | | | | | |

**Table 7** Search string Scopus and Web of Science

| | | | | | |
|---|---|---|---|---|---|
| Scopus | TITLE-ABS-KEY((homopolymer OR monopolymer OR "single plastic" OR mono-material OR "homogeneous polymer" OR "homogeneous plastic" OR multilayer OR multi-layer OR heteropolymer OR "heterogeneous polymer" OR "heterogeneous plastic" ) | **AND** | ( recycling OR reprocessing OR reusing OR recyclability OR circular ) | **AND** | ( "material properties" OR "mechanical properties" OR "tensile properties" OR "material degradation" )) |
| Web of Science | ((homopolymer OR monopolymer OR "single plastic" OR mono-material OR "homogeneous polymer" OR "homogeneous plastic" OR multilayer OR multi-layer OR heteropolymer OR "heterogeneous polymer" OR "heterogeneous plastic") | **AND** | ( recycling OR reprocessing OR reusing OR recyclability OR circular ) | **AND** | ( "material properties" OR "mechanical properties" OR "tensile properties" OR "material degradation" )) |

**Table 8** Mechanical properties of virgin and recycled material

| Authors, year | Polymer | Young's modulus MPa | | Tensile strength at yield MPa | | Tensile strength at break MPa | | Elongation at yield % | | Elongation at break % | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Virgin | Recycled | Virgin | Recycled | Virgin | Recycled | Virgin | Recycled | Virgin | Recycled |
| Ma & La Mantia, 1996 | PVC | 1860 | 1760 | 46* | 40* | 41* | 36* | 8* | 6* | 30* | 65* |
| Kukaleva et al., 2003 | HDPE | 860 | 1000 | 22.5 | 23.4 | - | - | - | - | >500 | 420 |
| Kaiser & Ginzinger, 2021 | LDPE | 206±13.6 | 133±12.8 | - | - | 31.3±1.56 | 28.9±0.74 | - | - | 201.9±38.1 | 244.1±26.0 |

**Table 9** Mechanical properties of homogeneous blends with increasing ratio of recycled content

| Authors, year | Homogeneous blends | Recycled material content | Young's modulus | Tensile strength | Tensile strength at yield | Tensile strength at break | Elongation at break |
|---|---|---|---|---|---|---|---|
| | | | MPa | MPa | MPa | MPa | % Before - After |
| Ma & La Mantia, 1996 | PVC | 0% | 1860 | - | 44* | 40* | 15* |
| | | 10% | 1850* | - | 44* | 40* | 10* |
| | | 20% | 1840* | - | 43* | 40* | 15* |
| | | 30% | 1830* | - | 42* | 39* | 18* |
| | | 40% | 1820* | - | 41* | 38* | 20* |
| | | 50% | 1800* | - | 40* | 37* | 30* |
| Scaffaro & La Mantia, 2002 | Nylon6 | 0% | 665* | 42,5* | - | - | 250* |
| | | 25% | 700* | 43,0* | - | - | 150* |
| | | 50% | 750* | 43,0* | - | - | 125* |
| | | 75% | 775* | 42,5* | - | - | 100* |
| | | 100% | 725* | 43,0* | - | - | 150* |
| Stoian et al., 2019 | PP | 0% | 1619.8 | - | - | 35.7 | 8.2 |
| | | 50% | 1387.5 | - | - | 31.0 | 10.0 |
| | | 60% | 1300.2 | - | - | 29.7 | 10.3 |
| | | 70% | 1244.5 | - | - | 27.7 | 10.4 |
| | | 80% | 1223.3 | - | - | 29.8 | 12.0 |
| | | 90% | 1162.9 | - | - | 27.1 | 18.3 |
| | | 100% | 1146.0 | - | - | 26.3 | 11.0 |
| Dobránsky et al., 2021 | PP | 0% | - | - | 34.4 | 16.2 | 9.79 - 97.6 |
| | | 10% | - | - | 34.7 | 16.1 | 9.78 - 97.2 |
| | | 20% | - | - | 34.8 | 15.9 | 9.81 - 96.3 |
| | | 30% | - | - | 35.2 | 15.8 | 9.89 - 94.5 |
| | | 50% | - | - | 35.3 | 15.8 | 9.93 - 93.4 |
| | | 70% | - | - | 35.0 | 15.8 | 9.92 - 92.9 |
| | | 100% | - | - | 35.2 | 15.9 | 9.99 - 92.1 |
| | | | | - | | | |
| Van Straten et al., 2021 | PP | 0% | 795 | 31.5 | - | - | 14* |
| | | 25% | 805* | 32* | - | - | 13* |
| | | 50% | 879 | 33* | - | - | 11.5* |
| | | 75% | 950* | 36* | - | - | 11.5* |
| | | 100% | 1021 | 36.5 | - | - | 8* |

**Table 10** Mechanical properties of homopolymers after multiple extrusion cycles

| Authors, year | Homopolymer | Extrusion cycles | Young's modulus | Tensile strength | Elongation at break |
|---|---|---|---|---|---|
| | | | MPa | MPa | % |
| Spinance et al., 2001 | PET | 0 | - | 63.0±2.9 | 112±23 |
| | | 1 | - | 60.0±1.6 | 167±42 |
| | | 2 | - | 60.0±1.7 | 140±45 |
| | | 3 | - | 52.0±2.9 | 6.0±0.7 |
| | | 4 | - | 54.0±2.0 | 6.0±0.2 |
| | | 5 | - | 55.0±2.2 | 6.0±0.3 |
| Van Kets et al., 2019 | PET | 1 | 2505 | 53.9 | 220* |
| | | 2 | 2400* | 52* | 200* |
| | | 3 | 2400* | 52* | 180* |
| | | 4 | 2500* | 54* | 180* |
| | | 5 | 2500* | 54* | 180* |
| Van Kets et al., 2019 | PP | 1 | 1444 | 32.0 | - |
| | | 2 | 1450* | 33* | - |
| | | 3 | 1450* | 32* | - |
| | | 4 | 1450* | 33* | - |
| | | 5 | 1450* | 33* | - |
| Vidakis et al., 2021 | PETG | 1 | 189.1 | 39.8±0.95 | - |
| | | 2 | 242.4±17.11 | 44.9±2.16 | - |
| | | 3 | 237.5±6,87 | 46.1±0.75 | - |
| | | 4 | 247.0±21.77 | 45.6±4.35 | - |
| | | 5 | 208.7±35.18 | 37.9±4.77 | - |
| | | 6 | 183.3±24.65 | 33.3±5.53 | - |
| La Mantia et al., 2021 | PP | 0 | 500* | 30* | 700* |
| | | 1 | 475* | 30* | 650* |
| | | 2 | 450* | 25* | 600* |
| | | 3 | 450* | 22,5* | 550* |
| | | 4 | 450* | 20* | 525* |
| | | 5 | 450* | 20* | 500* |
| La Mantia et al., 2021 | 70/30 PP | 0 | 500* | 30* | 700* |
| | | 1 | 475* | 30* | 650* |
| | | 2 | 450* | 30* | 650* |
| | | 3 | 400* | 28* | 625* |
| | | 4 | 400* | 28* | 625* |
| | | 5 | 400* | 28* | 600* |

**Table 11** Mechanical properties of heterogeneous blends and its constituents

| Authors, year | Polymer blends | Young's modulus | Tensile strength at break | Tensile strength at yield | Elongation at break |
|---|---|---|---|---|---|
| | | MPa | MPa | MPa | % |
| Guerrero et al., 2001 | PET | 2406±192 | 57,8±0.2 | | 20±1.6 |
| | HDPE | 1307±46 | 24.5±0.4 | | 628±102 |
| | 75/25 PET/HDPE | 2122±189 | 47.2±1.6 | | 2.6±0.2 |
| Kukaleva et al., 2003 | r-HDPE | 860 | - | 22.5 | >500 |
| | PP | 1200 | - | 31.8 | 500 |
| | LDPE | 125 | - | 12.1 | 95 |
| | 77/23 r-HDPE/PP | 1000* | - | 25* | - |
| | 77/18/5 r-HDPE/LDPE/PP | 800* | - | 25* | - |
| Nomura et al., 2020 | PET | 1960±150 | 39.4±1.1 | - | 235.6±32.1 |
| | LDPE | 220±20 | 24.9±3.4 | - | 840.4±87.3 |
| | PET/LDPE (80/20) | 1280±100 | 21.1±1.8 | - | 9.8±2.3 |

**Table 12** Mechanical properties of heterogeneous blends with increasing ratio of material

| Authors, year | Heterogeneous blends | Increasing content | Young's Modulus | Tensile Strength at yield | Elongation at yield | Elongation at break |
|---|---|---|---|---|---|---|
| | | | MPa | MPa | % | % |
| Nir et al., 1995 | LDPE/Nylon6 | 0% nylon6 | 200* | 10* | - | 250* |
| | | 20% nylon6 | 250* | 10* | - | 50* |
| | | 40% nylon6 | 450* | 17.5* | - | 70* |
| | | 60% nylon6 | 700* | 25* | - | 80* |
| | | 80% nylon6 | 900* | 40* | - | 90* |
| | | 100% nylon6 | 1100* | 45* | - | 100* |
| Uehara et al., 2015 | PE/PET | 0% PET | - | 20* | 25* | - |
| | | 25% PET | | 20* | 10* | - |
| | | 50% PET | | 25* | 7.5* | - |
| | | 75% PET | | 30* | 7.5* | - |
| | | 100% PET | | 60* | 10* | - |

**Table 13** Mechanical properties of heterogenous blends extruded multiple times

| Authors, year | Heterogeneous blend | Extrusion cycles | Young's modulus | Tensile strength at break | Elongation at break |
|---|---|---|---|---|---|
| | | | MPa | MPa | % |
| La Mantia & Capizzi et al., 2001 | 80/20 nylon6/PP | 1 | - | 30 | 30 |
| | | 2 | - | 32 | 41 |
| | | 3 | - | 31 | 45 |
| | | 4 | - | 31 | 48 |
| Van Kets et al., 2019 | 75/25 PP/PET | 1 | 1395 | 27.4 | 250* |
| | | 2 | 1390* | 27* | 150* |
| | | 3 | 1390* | 27* | 50* |
| | | 4 | 1390* | 27* | 50* |
| | | 5 | 1400* | 27* | 50* |