Challenges to using recycled High-density polyethylene materials for pipe manufacturing

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Lisa Erichs

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Lisa Erichs
MVEM14 Thesis for Degree of Master 30 hp, Lund University
Supervisor: Dr Jagdeep Singh, Centre for Environmental and Climate Science (CEC), Lund University
Assisting supervisor: Raül López I Losada, Centre for Environmental and Climate Science (CEC), Lund University

CEC - Centre for Environmental and Climate Science
Lund University
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Abstract

Recycling has become increasingly relevant to solve environmental problems related to the enormous amount of plastic waste. Recycling plastic has many environmental benefits, but it is challenging to find applications where recycled plastic can provide the same functionality as virgin plastic. This thesis highlights the challenges of using recycled High-density polyethylene (HDPE) in pipe applications. Additionally, the thesis addresses how the addition of recycled content in a blend may affect product quality and how different sources of recycled HDPE may affect the characteristics and quality of pressure pipes. HDPE plays a crucial role in the pipe industry since it is one of the most demanded plastics for manufacturing non-pressure and pressure pipes. The method involves literature review in two phases, one focusing on LCA studies on HDPE and the one on pipes made from HDPE. The initial search was made to include the entire life cycle of high pressure pipes made from HDPE and the second to include additional types of pressure pipes to gather insight if the allowed recycled content in manufacturing differ depending on pipe application.

The results suggest that the possibility of using recycled material in pipe manufacturing depends on several factors such as quantity of recycled content in the blend, pipe grade and designated application. It is challenging to incorporate recycled HDPE in plastic pipes since it may affect properties of the pipe. Additionally, the quality of the waste and the presence of contaminants and impurities can affect the quality of the pipe. However, using recycled material in pipe manufacturing can create environmental benefits such as reduced use of resources, less energy consumption and lower impact on acidification. This thesis provides insights into the role of recycled HDPE in the pipe industry and its potential to contribute to a more sustainable and circular economy.

Keywords: HDPE, Pressure pipe, Recycling, Properties

Populärvetenskaplig sammanfattning

Produktionen av plast är omfattande och plast förekommer nästan överallt i vardagen i en mängd olika produkter. Det finns många olika typer av plast, användningsområdena är flertaliga och ett liv utan plast skulle se väldigt annorlunda ut. Plast används bland annat vid tillverkning av kläder, leksaker och plaströr som exempelvis förser oss med rent vatten. Utan plast skulle vi inte ha någon el, inga mobiltelefoner och ingen tillgång till internet då plastisolerade ledningar förser oss med elektricitet. Utmärkande för de flesta plaster är att de är slitstarka och svårnedbrytbara, egenskaper som gör dem användbara men också skadliga för miljön.

Ett stort användningsområde för plast är rörtillverkning. Rör transporterar enorma mängder resurser såsom avloppsvatten och dricksvatten för sanitära system och används även för hushåll och kommunala reningsverk samt inom jordbruket. I tryckrör är högdensitets polyeten (HDPE) den vanligaste plasten för tillverkning och HDPE har egenskaper som är praktiska för en rad olika rör, bland annat dräneringsrör, vattenrör och gasledningar. För att tillverka HDPE krävs betydande mängder energi och råmaterial vilket påverkar miljön negativt. Återvinning av plasten kan leda till mindre resursutnyttjande och en minskad mängd plastavfall på deponier. Att återvinna plasten för att använda den igen vid tillverkning av rör kan dessutom innebära kostnadsbesparingar jämfört med tillverkning med jungfrulig plast. Forskare och plasttillverkare stöter dock på en del hinder kring utvecklingen av plaståtervinning med syfte att återanvändas vid tillverkningen av tryckrör:

- Under återvinningsprocessen kan HDPE bli kontaminerat av andra material, såsom andra plastsorter och kemikalier, vilket försvagar materialet och försämrar kvaliteten av röret.
- Blandningen av återvunnet material och jungfruligt material kan påverka plaströrens egenskaper.
- Avfallskällan har stor betydelse för den slutliga kvaliteten av röret vilket kan påverka dess prestanda och hållbarhet.
- Eftersom plastavfall är av varierande kvalitet kan utbudet inte alltid vara stort vilket gör det svårt att få tag på duglig plast

Med en litteraturstudie i två faser som utgångspunkt ämnar denna uppsats att belysa möjligheterna att använda återvunnen HDPE vid tillverkningen av plaströr.

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1. Introduction

Global plastic use has increased rapidly, and 300 million tons of plastic waste is produced every year (Ellen MacArthur Foundation, 2017). In the United States plastic waste in the municipal solid waste stream increased from less than 1% in 1960 to 12.7% in 2012 which is an issue since the production rate of virgin plastic is significantly higher than the recycling rate (Beheshtian Ardakani et al., 2018). Geyer et al. (2017) predicts that 12,000 Mt of global plastic waste will be in landfills or in the natural environment by 2050 if current production and waste management trends continue. The contamination of the natural environment with plastic waste is a growing concern and the commonly used plastics are not biodegradable, which means they accumulate (Geyer et al., 2017). Plastic debris is contaminating all major ocean basins, freshwater systems, and terrestrial habitats (Geyer et al., 2017). Microplastics have been found in various environments and impose a threat to organisms since they can enter the food chain and cause ecological imbalances (Free et al., 2014). Additionally, microplastics have been found in the air and in food destined for human consumption (Wright & Kelly, 2017). Thus, exposure via diet or inhalation could occur and possibly affect human health (Wright & Kelly, 2017).

Plastic waste can be treated in different ways such as disposal, incineration, or through recycling processes (Istrate et al., 2021; Mannheim, 2021). From the estimated 6300 million metric tons (Mt) plastic waste generated up to 2015, only 9 percent was recycled, 12 percent was incinerated, and 79 percent was accumulated in landfills or in the natural environment (Geyer et al., 2017). Mechanical recycling is a common method of plastic recycling that includes the following steps: cutting or shredding, contaminant separation and flakes separation, which are followed by granulating the material by processing and milling (Singh et al., 2017). To remove glue particles, the material is then pre-washed and dried (Singh et al., 2017).

Despite the challenges associated with waste, the European Union prioritizes extending the life cycle of products as a circular economy strategy to prevent waste (European Commission, 2018; Faraca et al., 2019; Mannheim, 2021). Efficient resource management and waste prevention lower the greenhouse gas emissions and minimizes material and energy use (Mannheim, 2021; Sabaliauskaité & Kliaugaité, 2014). Today many stakeholders are considering the consequences of materials used in products and their EoL management (Simões et al., 2014). According to Bicalho et al. (2017), LCA can be used to evaluate and compare the environmental impact of virgin and recycled plastics. They point out that LCA allows companies to identify, assess, consolidate, interpret, and disseminate data on the environmental impacts generated by their actions. Since LCA includes the environmental impact of all stages of a product's life cycle from raw materials extraction to the product's end of life (EoL) stage, it can improve management and decision making within the company (Bicalho et al., 2017). This can lead to the company achieving cleaner production and environmental and financial savings (Bicalho et al., 2017).

1.1 Production

Polyethylene (PE) is a versatile material combining exceptional functionality with low cost and with many fields of application (Ellen MacArthur Foundation, 2017; Juan et al., 2020). Because of the versatility, it is not easy to find replacement materials with the same characteristics. However, the increasing production of virgin PE results in more waste which has a negative impact on the environment if not handled properly (Juan et al., 2020). The generation of plastic waste means that material will go to waste, more virgin materials need to be extracted and emissions will keep increasing to produce more plastic (Juan et al., 2020). PE is one of seven families of 'commodity thermoplastic' polymers that account for around 70% of plastic production in North America and is the largest contributor to plastic waste in the world, which is illustrated by Geyer (2020) in Figure 1 (Geyer, 2020; Posen et al., 2017).

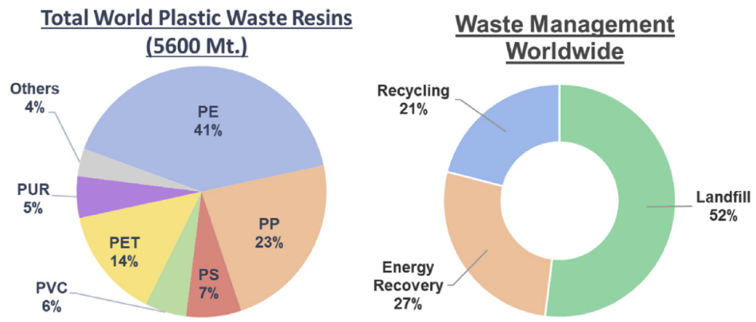

Figure 1 Plastic Waste Resins Worldwide
World Plastic Waste Resins generated by the end of 2018 and estimated Waste Management rates for these resins, as taken from (Geyer, 2020).

The PE-family includes High-density polyethylene HDPE, low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE) (Posen et al., 2017). HDPE is a type of PE that is prepared at lower temperature and pressure with a modified structure and it is one of the most demanded plastics within the construction industry, especially for non-pressure and pressure pipes (Juan et al., 2020; Ronca, 2017). Products, such as pipes, are produced with HDPE granules that are shown in Figure 2 (Alzerreca et al., 2015). When manufacturing with recycled material plastic waste from different sources is recycled and granulated (Alzerreca et al., 2015).

Figure 2 Plastic Granules
Plastic Granules. From Polyethylene Balls, By Lluis tgn, Wikimedia. Reprinted with permission. (https://commons.wikimedia.org/wiki/File:Polyethylene_balls1.jpg). CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0/deed.en)

In addition to pipe applications, such as pipelines for water transportation (shown in Figure 3), HDPE is also used to produce safety devices, bags, cups, meshes, nets and grids for product protection (Alzerreca et al., 2015; Du et al., 2013; Nguyen et al., 2020; Ronca, 2017; Simões et al., 2020; Singh et al., 2017). It is a thermoplastic that imposes environmental burdens when produced and environmental costs at end of life (EoL) (Nguyen et al., 2020). According to Sangwan & Bhakar (2017), HDPE is a thermoplastic with relatively low production cost and pipes made from HDPE have a wide variety of pipe applications such as municipal, industrial, underwater, landfill gas extraction, cable duct, mining, and agriculture. Additionally, they state that HDPE has a low repair frequency per km per pipe per year relative to other pipe materials used for urban water and gas distribution. Pipes made from HDPE are known to be durable and are designed to have a long service life, often exceeding 50 years (Alzerreca et al., 2015; Beheshtian Ardakani et al., 2015; Nguyen et al., 2023).

Figure 3 HDPE Pipeline used for water transportation
HDPE Pipeline used for water transportation. From HDPE Pipeline in a harch Australian environment, used for transporting water to a mine site, by Gordon J86, Wikimedia. Reprinted with permission.
(https://commons.wikimedia.org/wiki/File:HDPE_Pipeline_in_a_harsh_Australian_environment.jpg)

1.2 Previous studies

Several studies highlight the issue of plastic waste accumulating in the environment, affecting oceans and terrestrial habitats while investigating the possibilities of replacing plastic with other renewable materials. However, replacing plastic with other materials may result in exploitation of other resources and other issues such as emissions contributing to the greenhouse effect (Naturvårdsverket, 2018). According to Istrate et al. (2021), one of the challenges of manufacturing pipes with recycled HDPE is being able to incorporate the recycled material which means it is not common within the pipe industry and therefore there is a lack of research. Several studies have also compared the environmental impact of commonly used plastics within the pipe industry, rather than specifically recycled plastic (Istrate et al., 2021). Poduška et al. (2019) assessed the possibility of combining recycled HDPE layers with virgin HDPE layers in PE pressure pipes, and Juan et al. (2020) evaluated potential use of recycled HDPE from various sources in the manufacture of PE pressure pipes. Replacing part of the HDPE raw material with recycled material would enhance the circular economy by closing the loop on HDPE for pipe application (Juan et al., 2020). Several studies have used Life Cycle Assessment (LCA) to compare the environmental impacts of commonly used materials for pipe applications, including HDPE. Petit-Boix et al. (2014) for example analyzed the construction impact of different virgin pipe materials, comparing different stages of the life cycle's impact. Studies of construction impact are of relevance with the ongoing increase of urban population. However little attention has been paid to the environmental impacts of incorporating recycled HDPE into pipes.

1.4 The Waste Hierarchy

The Waste Hierarchy ranks waste management options according to what is best for the environment where the top priority is preventing waste (Defra, 2011). Re-use and recycling are the following priorities and disposal is last (Defra, 2011). Finding solutions for plastic recycling is important to avoid its landfill disposal. Since plastic has a negative impact on the environment, the study is relevant to investigate possibilities for recycling plastic, specifically HDPE, and thus reducing the raw material extraction and the emissions that occur during the manufacturing of plastic. In addition, ISO 14001 describes the reuse and recycling of materials as both an internal and external measure that companies should take to prevent pollution.

Manufacturing of pressure pipes from recycled HDPE keeps the material in a circular flow instead of replacing it with other materials. This thesis is written in collaboration with Esvama, whose customers include pipe manufacturers and the main application for recycled HDPE will be within pipe manufacturing.

1.5 Aim and Research Questions

This thesis aims to facilitate decision-making regarding recycling of HDPE by investigating the possibility to manufacture pressure pipes from recycled HDPE instead of virgin HDPE, while fulfilling existing requirements for such pipes. Features of HDPE are analyzed and possibilities of recycling HDPE for manufacturing of pressure pipes to maintain it in a circular flow instead of replacing it with other materials are highlighted. The analysis considers an LCA perspective, which is important to avoid trade-offs between life cycle stages. The results can be used by manufacturers that want to investigate the possibilities of using recycled HDPE in their production as a replacement or complement to virgin HDPE. Additionally, decision makers can use the results as guidance in investigations into environmental risks linked to the manufacture of HDPE and plastic waste.

The research questions for this thesis are:

- What are the challenges of using recycled HDPE in pipe applications?
- How do different sources of recycled HDPE for pipe manufacturing affect the characteristics and the quality of the pipe?
- How does blending affect the quality of pipes?

1.6 Limitations

This thesis is limited to the study of pressure pipes made from HDPE, because Esvama purchases and distributes plastic granules to pressure pipe manufacturers. However, studies of other types of pipes have been included to broaden the insight of recycling possibilities within the pipe industry. The main material group to produce these types of pipes is HDPE which is why the thesis is limited to highlighting HDPE as the production material. Furthermore, mechanical recycling is the most common method for recycling plastic (Alzerreca et al., 2015) and the thesis is limited to highlighting mechanical recycling.

2. Method

To answer the research questions, the following method was used:

- To find scientific basis for this thesis, a literature review in two phases was carried out. All the material for the literature review was obtained from the search database Web of Science. To limit the results, search terms identified in literature within the subject were used. Keyword combinations used for online searches are shown in Table 1 a-e. To achieve the purpose of the study and to include the entire life cycle of the products, articles in the first phase of the literature review involved LCA.
- Since the main application for recycled HDPE is within pipe manufacturing in this thesis, the second phase included an additional search that was made to gather more information within this specific field. Search words were identified from the articles in the initial phase of the literature review and complemented with additional types of pipes to broaden the insights (see Table 2). The addition of this search was made to include more relevant information. According to Hart (2018) this is important to broaden the collection of information.

Table 1 a Search Schedule in Web of Science focused on LCA studies on HDPE
Search Schedule in Web of Science for scientific articles that are included in the search for the literature review focused on LCA of HDPE used in pipe application.

Databas, date Web of Science	Search terms	Limitations	Number of studies
#1 **2023-01-19**	Title: ("HDPE" OR "plastic product*" OR "High-density polyethylene" OR "polyethylene high-density" OR "High density polyethylene" OR "polyethylene high density" OR "polyethene" OR "Fossil based plastic*"OR "Fossil-based plastic*" OR "virgin plastic*") AND Topic: ("LCA" OR "life cycle assessment*" OR "Life cycle analysis" OR "life-cycle*" OR "carbon footprint" OR "climate impact" OR "greenhouse gas emission*" OR "GHG emission*" OR "plastic pollution*") AND Topic: ("recyc*" OR "mechanical recyc*" OR "Plastic granul*" OR "plastic pipe*" OR "plastic-pipe*" OR "HDPE")		74

Table 1 b Search Schedule in Web of Science focused on LCA studies on HDPE
Search Schedule in Web of Science for scientific articles that are included in the search for the literature review focused on LCA of HDPE used in pipe application.

Databas, date Web of Science	Search terms	Limitations	Number of studies
#2 **2023-01-25**	Title: ("HDPE" OR "plastic product*" OR "High-density polyethylene" OR "polyethylene high-density" OR "High density polyethylene" OR "polyethylene high density" OR "polyethene" OR "Fossil based plastic*" OR "virgin plastic*") AND Topic: ("LCA" OR "life cycle assessment*" OR "life cycle impact assessment*" OR "Life cycle analysis" OR "life-cycle*" OR "carbon footprint" OR "climate impact" OR "environmen* impact" OR "greenhouse gas emission*" OR "GHG emission*" OR "plastic pollution*") AND Topic: ("recyc*" OR "mechanical recyc*" OR "Plastic granul*" OR "polymer granul*" OR "HDPE pipe*" OR "HDPE tube*" OR "tube extruder*" OR "tube*" OR "plastic tube*" OR "plastic pipe*" OR "plastic-pipe*" OR "HDPE flake*" OR "mixed-plastic product*" NOT chemical recyc*)	Filter: Article & Review Article	58

Table 1 c Search Schedule in Web of Science focused on LCA studies on HDPE
Search Schedule in Web of Science for scientific articles that are included in the search for the literature review focused on LCA of HDPE used in pipe application.

Databas, date Web of Science	Search terms	Limitations	Number of studies
#3 **2023-01-25**	Topic: ("plastic product*" OR "polyethylene" OR "PE" OR "HDPE" OR "High-density polyethylene" OR "polyethylene high-density" OR "High density polyethylene" OR "polyethylene high density" OR "polyethylene" OR "Fossil based plastic*" OR "virgin plastic*") AND Topic: ("LCA" OR "life cycle assessment*" OR "life cycle impact assessment*" OR "Life cycle analysis" OR "life-cycle*" OR "sustainable business model*" OR "carbon footprint" OR "climate impact" OR "environmen* impact" OR "greenhouse gas emission*" OR "GHG emission*" OR "plastic pollution*") AND Topic: ("virgin HDPE" OR "recyc* HDPE" OR "virgin polyethylene" OR "virgin HDPE" OR "virgin High-density polyethylene" OR "virgin polyethylene high-density" OR "recyc* polyethylene" OR "recyc* PE" OR "recyc* High-density polyethylene" OR "recyc* polyethylene high-density" OR" Plastic granul*" OR "polymer granul*" OR "HDPE pipe*" OR "HDPE tube*" OR "tube extruder*" OR "tube*" OR "plastic tube*" OR "plastic pipe*" OR "plastic-pipe*" OR "HDPE flake*" OR "homogeneous plastic*" OR "mixed-plastic product*" OR "post-consumer plastic*") AND Topic: ("recyc*" OR "mechanical recyc*" NOT chemical recyc*)	Filter: Article & Review Article	116

Table 1 d Search Schedule in Web of Science focused on LCA studies on HDPE
Search Schedule in Web of Science for scientific articles that are included in the search for the literature review focused on LCA of HDPE used in pipe application.

Databas, date Web of Science	Search terms	Limitations	Number of studies
#4 **2023-02-04**	Topic: ("plastic product*" OR "resin*" OR "polyethylene" OR "PE" OR "HDPE" OR "High-density polyethylene" OR "polyethylene high-density" OR "High density polyethylene" OR "polyethylene high density" OR "polyethylene" OR "Fossil based plastic*" OR "virgin plastic*") AND Topic: ("LCA" OR "life cycle assessment*" OR "life cycle impact assessment*" OR "Life cycle analysis" OR "life-cycle*" OR "sustainable business model*" OR "carbon footprint" OR "climate impact" OR "environmen* impact" OR "greenhouse gas emission*" OR "GHG emission*" OR "plastic pollution*" OR "climate impact" OR "environmen* impact" OR "greenhouse gas emission*" OR "GHG emission*" OR "plastic pollution*") AND Topic: ("virgin HDPE" OR "recyc* HDPE" OR "recyc* polyethylene" OR "recyc* PE" OR "recyc* High-density polyethylene" OR "recyc* polyethylene high-density" OR "homogeneous plastic*" OR "mixed-plastic product*" OR "post-consumer plastic*") AND Topic: ("recyc*" OR "mechanical recyc*" NOT chemical recyc*)	Filter: Article & Review Article	104

Table 1 e Search Schedule in Web of Science focused on LCA studies on HDPE
Search Schedule in Web of Science for scientific articles that are included in the search for the literature review focused on LCA of HDPE used in pipe application.

Databas, date Web of Science	Search terms	Limitations	Number of studies
#5 23-03-06	Topic: ("HDPE" OR "High-density polyethylene" OR "High density polyethylene" OR "High-density PE" OR "High density PE" OR "polyethylene high-density" OR "polyethylene high density" OR "PE High-density" OR "PE High density" OR "virgin HDPE" OR "pristine HDPE" OR "fossil HDPE" OR "fossil based HDPE" OR "fossil-based HDPE" OR "pristine HDPE" OR "fossil High-density polyethylene" OR "fossil based High-density polyethylene" OR "fossil-based High-density polyethylene" OR "virgin High density polyethylene" OR "pristine High density polyethylene" OR "fossil High density polyethylene" OR "fossil based High density polyethylene" OR "fossil-based High density polyethylene" OR "virgin High-density PE" OR "pristine High-density PE" OR "fossil High-density PE" OR "fossil based High-density PE" OR "fossil-based High-density PE" OR "pristine High-density PE" OR "virgin High density PE" OR "pristine High density PE" OR "fossil High density PE" OR "fossil based High density PE" OR "fossil-based High density PE" OR "pristine High density PE" OR "virgin polyethylene high-density" OR "pristine polyethylene high-density" OR "fossil polyethylene high-density" OR "fossil based polyethylene high-density" OR "fossil-based polyethylene high-density" OR "pristine polyethylene high-density" OR "virgin "polyethylene high density" OR "pristine "polyethylene high density" OR "fossil polyethylene high density" OR "fossil based polyethylene high density" OR "fossil-based polyethylene high density" OR "pristine polyethylene high density" OR "virgin PE High-density" OR "pristine PE High-density" OR "fossil PE High-density" OR "fossil based PE High-density" OR "fossil-based PE High-density" OR "pristine PE High-density" OR "virgin PE High density" OR "pristine PE High density" OR "fossil PE High density" OR "fossil based PE High density" OR "fossil-based PE High density" OR "pristine PE High density") AND Topic: ("LCA" OR "life cycle assessment*" OR "life cycle impact assessment*" OR "Life cycle analysis" OR "life-cycle*" OR "sustainable business model*" OR "carbon footprint" OR "climate impact*" OR "environmen* impact" OR "greenhouse gas emission*" OR "GHG emission*" OR "plastic pollut*") AND Topic: ("recyc* HDPE" OR "recyc* High-density polyethylene" OR "recyc* polyethylene high-density" OR "recyc* PE High-density" OR "recyc* PE High density" OR "post-consumer HDPE" OR "post consumer HDPE" OR "post-consumer High-density polyethylene" OR "post consumer High-density polyethylene" OR "post-consumer polyethylene high-density" OR "post consumer polyethylene high-density" OR "post-consumer PE High-density" OR "post consumer PE High-density" OR "post-consumer PE High density" OR "post consumer PE High density") AND Topic: ("recyc*" OR "mechanical recyc*") NOT Topic: (chemical recyc*)	Filter: Article	27

Table 2 Search Schedule in Web of Science focused on pipes made from HDPE

Search Schedule in Web of Science for scientific articles that are included in the search for the literature review focused on LCA of HDPE used in pipe application.

Databas, date Web of Science	Search terms	Limitations	Number of studies
#1 23-03-06	Topic: ("HDPE" OR "High-density polyethylene" OR "High density polyethylene" OR "High-density PE" OR "High density PE" OR "polyethylene high-density" OR "polyethylene high density" OR "PE High-density" OR "PE High density" OR "virgin HDPE" OR "pristine HDPE" OR "fossil HDPE" OR "fossil based HDPE" OR "fossil-based HDPE" OR "pristine HDPE" OR "fossil High-density polyethylene" OR "fossil based High-density polyethylene" OR "fossil-based High-density polyethylene" OR "virgin High density polyethylene" OR "pristine High density polyethylene" OR "fossil High density polyethylene" OR "fossil based High density polyethylene" OR "fossil-based High density polyethylene" OR "virgin High-density PE" OR "pristine High-density PE" OR "fossil High-density PE" OR "fossil based High-density PE" OR "fossil-based High-density PE" OR "pristine High-density PE" OR "virgin High density PE" OR "pristine High density PE" OR "fossil High density PE" OR "fossil based High density PE" OR "fossil-based High density PE" OR "pristine High density PE" OR "virgin polyethylene high-density" OR "pristine polyethylene high-density" OR "fossil polyethylene high-density" OR "fossil based polyethylene high-density" OR "fossil-based polyethylene high-density" OR "pristine polyethylene high-density" OR "virgin "polyethylene high density" OR "pristine "polyethylene high density" OR "fossil polyethylene high density" OR "fossil based polyethylene high density" OR "fossil-based polyethylene high density" OR "pristine polyethylene high density" OR "virgin PE High-density" OR "pristine PE High-density" OR "fossil PE High-density" OR "fossil based PE High-density" OR "fossil-based PE High-density" OR "pristine PE High-density" OR "virgin PE High density" OR "pristine PE High density" OR "fossil PE High density" OR "fossil based PE High density" OR "fossil-based PE High density" OR "pristine PE High density") AND Topic: ("pipe line*" OR "pipeline*" OR "industrial pipeline*" OR "industrial pipe line*" OR "municipal pipeline*" OR "municipal pipeline*" OR "cable*" OR "protective tube*" "protective pipe" OR "tube*" OR "drain* pipe*" OR "drainage pipe*" OR "drain*" OR "drain* tube*" OR "pipe*" OR "pipe applica*" OR "pressure pipe*" OR "pressure tube*" OR "water pipe*" OR "water tube*" OR "gas pipe*" OR "gas tube*" OR "HDPE pipe*" OR "High-density polyethylene pipe*" OR "High density polyethylene pipe*" OR "HDPE pipe manufacturing" OR "pipe grade*" OR "resin" OR "PE100" OR "PE80" OR "PE63" OR PE40" OR "PE32" OR "PE 100" OR "PE 80" OR "PE 63" OR PE 40" OR "PE 32") AND Topic: ("recyc* HDPE" OR "recyc* High-density polyethylene" OR "recyc* polyethylene high-density" OR "recyc* PE High-density" OR "recyc* PE High density" OR "post-consumer HDPE" OR "post consumer HDPE" OR "post-consumer High-density polyethylene" OR "post consumer High-density polyethylene" OR "post-consumer polyethylene high-density" OR "post consumer polyethylene high-density" OR "post-consumer PE High-density" OR "post consumer PE High-density" OR "post-consumer PE High density" OR "post consumer PE High density") AND Topic: ("recyc*" OR "mechanical recyc*") NOT Topic: ("chemic* recyc*")	Filter: Article & Review Article	49

Principles for selection and relevance assessment in the literature search

The process of carrying out a literature review includes different activities such as determination of key words, search, selection, assessment, and compilation (Höst et al., 2006). The criteria for including articles should be broad enough to encompass the likely diversity of the studies but narrow enough to assure that a relevant result can be obtained when studies are compared (Higgins et al., 2022). Similarly, Hart (2018) explains that the search needs to be narrow to avoid too much literature. To get an overall view of the knowledge in the area for this study an initial, more general, search in Web of Science was conducted to find relevant search terms. These search terms were selected to accurately describe the content relevant to this thesis. According to Hart (2018) a literature review should be initiated with searching for relevant sources and reading with a purpose to extract materials based on themes. The chosen search terms were combined a certain way which is shown in Table 1. All articles that were included in the literature review have undergone scientific review. This is of great importance for the credibility of the study (Höst et al., 2016). According to Geyer et al. (2017) plastic has been produced in large-scale since around 1950 and Gandhi et al. (2021) points out that plastic production has been increasing rapidly since 1950. Thus, only articles published after 1950 were included.

In the selection of articles from the search different criteria was used. Selected articles included HDPE as the material for the product and incorporating both virgin and recycled plastic. Some of Esvama's customers are pipe extruders that Esvama provides with HDPE. Thus, articles that involved LCA of products with HDPE that are very different compared to pipes were excluded. Such products may be film used for wrapping and other types of plastics that require different characteristics compared to the ones used in pipe application. However, some other product types were included in a few of the articles which were also read to gain a broader insight of the overall challenges regarding recycling. In addition, other search terms such as "climate impact", "environmen* impact" and "GHG emission" were used to include studies that evaluate relevant environmental impacts of HDPE from other perspectives or methods. In the literature, many authors compare virgin plastic with bio-based plastic. To avoid mainly results of studies comparing exclusively these, the search included search terms of specifically virgin and recycled plastic. However, some of the articles that were selected and used in the literature review include bio-based plastic in addition to recycled and virgin plastic. Furthermore, the articles included recycling. More specifically, mechanical recycling was included while chemical recycling was excluded since mechanical recycling is a more common method (Alzerreca et al., 2015).

The search in the first phase resulted in 27 articles. The abstract of all 27 articles was read thoroughly and the remaining text was read briefly to confirm that no relevant information was excluded unintentionally. Based on the criteria, 21 articles were included, and 6 articles were excluded. The 21 articles that remained after the first selection were read in depth. Each article was summarized and the content relevant to the scientific questions were highlighted. The main features were color-coded and relevant content in the articles was marked with the respective colors of the main topic. The search was filtered with article and all years were selected since every study was published after 1950. Additionally, according to Baumann & Tillman (2003) the 1990's was a period of harmonization of the LCA methodology and the first guidelines for LCA were published 1993. Thus, articles involving LCA that were included in this thesis were published after 1993.

For the additional search to gather more detailed information about virgin and recycled HDPE within the pipe industry, search words were identified during the initial phase of the literature search. These search words were complemented with additional search terms referring to different types of pipes to broaden this specific perspective. In this search, non-pressure pipes, low-pressure pipes and high-pressure pipes were included with the purpose of finding out whether the allowed recycled content may differ between the three. Additionally, several pipe grades were included for the same reason. This search resulted in 48 articles. The abstract of the 48 articles was read and based on criteria of only including studies of pipes made from HDPE 19 were read in depth. In this search studies on pipes made from other materials, such as metal, were excluded. Additionally, studies of other types of processes apart from recycling were excluded.

2.1 Ethical considerations

While using LCA as an evaluation method, too much aggregation can hide relevant information while too little aggregation drowns the information in too much detail (Baumann, 2003). LCA is complex and results can be presented in different ways, e.g., inventory results, characterisation results or weighted together (Baumann, 2003). Thus, it is of great importance that the material in this thesis is elaborated in such a way that it cannot be interpreted unfairly. Since this thesis is built on a literature review only the material collected from the search has been studied. This means that not all the data available on the subject has been evaluated and studied.

To test properties and quality of blends with different ratios of virgin and recycled HDPE different measurements are made. Just like in any other situation where measurements are involved it is of great importance that they are precise and carefully conducted to successfully measure what is intended. This is something that is impossible for the author of this thesis to control since the assessments and measurements are made by others.

To fulfill the aim, no personal information has been collected and there are no conflicts of interest to declare. Additionally, the scientific references that have been used do not discriminate between gender, culture, or background.

3. Results

The results indicate that there are several challenges to using recycled material in pipes. However, there are also several advantages and developing technology and new techniques of recycling is of great importance to the plastic and the pressure pipe industry to become more circular. In Table 3 and Table 4 (see page 28) the main challenges, and the positive effects of using recycled material in pipe application are summarized. In the following results these sections will be presented further.

Table 3 Summary of challenges
Summary of the main challenges of using recycled material in pipe applications that have been identified.

Challenges to recycling and use of recycled material	**Explanation**
Properties	Incorporation of recycled HDPE for pipe manufacturing may affect properties such as Rapid Crack Propagation, Slow Crack Growth, stiffness, Elongation at break, Tensile strength at yield and Flexural modulus (Domínguez, 2009; Istrate et al., 2021; Juan et al., 2020; Moser and Folkman, 2008; Nguyen et al., 2020).
Impurities and contaminants	Impurities and contaminants are present in recycled HDPE which may affect properties that lead to formation of crazes during stress. Additionally, contaminants are added while sorting recyclable HDPE which may affect the quality of the final product and create other issues (Beheshtian Ardakani et al., 2018; Juan et al., 2020; Simões et al., 2014).
Efficiency of waste management	Factors such as the distance to recovery facilities and the transportation logistics have an impact on the success of recycling. Additionally, the method of handling, sorting, separation, and selection of the plastic waste is important to achieve required pipe specifications and to increase the percentage of recycled HDPE into final products (Juan et al., 2020; Nguyen et al., 2020).
Quality of the waste	Plastic waste of lower quality results in contamination of the recycled material. Thus, improvements of the sorting of HDPE recovered from waste can reduce the degree of contamination (Juan et al., 2020; Perugini et al., 2005).

3.1 Challenges to using recycled materials for pipe manufacturing

3.1.1 Product properties

Recycling plastic waste results in a range of environmental benefits, but recycled plastic is a complex and heterogeneous material and may not provide the same functionality as virgin plastics. In consequence it is important to identify strategies to substitute virgin plastic for recycled plastic, while maintaining functionality (Faraca et al., 2019; Istrate et al., 2021). The physicochemical properties of the polymer, the processing conditions and the purity of the input waste affect the quality of the recycled plastic product (Faraca et al., 2019; Mannheim, 2021).

Manufacturing standards in the pipe industry recommend against the use of recycled materials which Alzerreca et al. (2015) argues depends on poor understanding of the properties and long-term mechanical performance of such materials. According to Juan et al. (2020) current EN and ISO standards should be revised soon to allow introducing recycled PEs. Although, recycled PE is currently being utilized to manufacture non-pressure or low-pressure pipes used for gardening or agriculture among other things (Juan et al., 2020; Singh et al., 2017). Poduška et al. (2019) assume that the use of recycled materials for pressure pipes will be allowed eventually even though it is not allowed according to current regulations.

According to Juan et al. (2020) recycling processes can lead to chain scission, branching and cross linking caused by thermomechanical degradation of the materials due to the deterioration of properties during reprocessing. These results are similar to those reported by Isaacson et al. (2020) who found that thermal degradation can cause contamination of the surrounding substances, such as water. Furthermore, the degradation influences crystallinity which affects the properties of the materials, such as stiffness or elongation at break (Juan et al., 2020). This results in restrictions in the use of recycled plastics, especially in some sectors (Juan et al., 2020). Additionally, Nguyen et al. (2020) mention that crystallinity and fracture energy are properties that require higher qualities of material in recycled HDPE compared to virgin HDPE to extend the pipe service lifetime (Nguyen et al., 2020). For pipes that are buried quite deep in the ground, pipe stiffness and pipe strength are important design parameters due to higher soil pressure (Moser and Folkman, 2008). For example, Beheshtian Ardakani et al. (2015) mention that landfill leachate collection pipes need to have enough strength to support the weight of overlying waste, cover system, and post-closure loadings. Furthermore, they mention that the pipes must withstand the stresses caused by the vehicles passing during construction and operating hours.

Slow Crack Growth (SCG) and Rapid Crack Propagation (RCP) are two key properties that are required in pipe application (Istrate et al.,2021; Juan et al., 2020;

Nguyen et al., 2020). In the case of pipe grade PE80 and PE100, both SCG and RCP are sensitive to the recycled content (Istrate et al., 2021). Additionally, the mechanical properties of the polymer can be reduced when polymers experience several thermal cycles to the melting temperature for mechanical recycling (Greene, 2014). However, Juan et al. (2020) mention that minimum requirements for properties such as tensile strength at yield, elongation at break and flexural modulus can be met for a blend with recycled and virgin HDPE for PE100 grades. A comparison between virgin, post-manufacturer, and post-consumer HDPE compounds provided by producers of plastic pipes, confirms that current recycling processes can result in production of recyclable compounds with acceptable quality for pipe applications (Alzerreca et al., 2015).

3.1.1.1 Enhancement of properties

Pipes made from PE generally contain added colorants, stabilizers, fillers, antioxidants and other essential ingredients to achieve desired properties that strengthen and protect the pipes during manufacturing and service (Diera et al., 2023). To enhance the mechanical and physical properties of the polymer and extend the lifetime of a pipe, Nguyen et al. (2020) suggests that a small concentration of nanoclay can be blended with recycled material. This may result in stress cracking resistance and prolonging of the polymer failure time (Na et al., 2016; Wang et al., 2006). The nanoclay production is energy intensive but very small quantities are needed to improve the polymer properties (Na et al., 2016; Nguyen et al., 2017). Similarly, de Oliveira Sampaio & Pimentel Real (2012) point out that it is necessary to blend the recycled content with virgin materials and additives to maintain the required properties. Due to the degradation of plastic products chemicals, including such additives, can migrate into the water that is transported through the pipes for example (Tang et al., 2015). These additives can be plasticizers (which is one of the most controversial additives), anticorrosive or antioxidant coatings (Tang et al., 2015). However, Oliveira Sampaio & Pimentel Real (2012) highlight that reuse of recycled polymers in plastic pipes is important from an environmental and economical point of view. The results of Oliveira Sampaio & Pimentel Real (2012) can be linked to the ones from Juan et al. (2020) who found that the use of natural fibers such as sisal and jute can reinforce polyethylene. Additionally, it is common that minor amounts of polypropylene are present in the PE waste streams and compatibilizers can address the mixture integration to reduce the negative effect of immiscible materials in the polymer matrix (Juan et al., 2020). Such compatibilizers may be nanoparticles which according to Maris et al. (2018) are cheap, non-specific compatibilizers for polymer blend systems and a good alternative in response to industrial issues for recycling blends.

3.1.2 Impurities and contamination

Recycled HDPE often shows lower mechanical performance due to degradation and contamination (Juan et al., 2020). The presence of impurities and contaminants of different sizes and shapes in recycled HDPE can affect properties such as SCG resistance and lead to craze openings and propagation (Juan et al., 2020). The SCG involves the formation of a craze at a point of stress concentration (Creton et al., 1992; Domínguez, 2009). Additionally, contaminants are added while sorting recyclable HDPE which may affect the quality of the final product and create other environmental or economic issues (Beheshtian Ardakani et al., 2018). Because of the favorable properties of PE pipes they are often used to transport water (Diera et al., 2023). However, according to Diera et al. (2023) compounds can migrate from the PE pipes to the water. Materials in contact with drinking water can release unwanted compounds which can affect odor and taste, cause microbial growth, or in worst case, be toxic (Diera et al., 2023). Alzerreca et al. (2015) found that recycled HDPE contains metallic residues and other inorganic contaminants. They found that the main contaminants are titanium and calcium. Calcium is a common filler substance in thermoplastics and may therefore be expected to be detected in HDPE (Alzerreca et al., 2015). Alzerreca et al. (2015) also detected other metals such as iron and zinc. Additionally, Isaacson et al. (2020) found that HDPE pipes exposed to high temperatures can generate benzene, toluene, ethylbenzene, and xylene which can leach from cooled plastics into the water. These temperatures might be reached when a fire in the surroundings takes place for example (Isaacson et al., 2020). A possible improvement to the material qualities of recycled HDPE is to minimize the amount of contaminants which is why plastic waste usually requires washing, cleaning, and purifying steps to reduce and prevent contamination in the recycled polymer (Alzerreca et al., 2015; Juan et al., 2020).

According to Istrate et al. (2021) waste from households generally contain a certain level of impurities while waste from e.g., industry and car scrapping is very pure and allow for a higher recycled content in pipe applications. Similarly, Juan et al. (2020) mention that plastic waste that is sourced from controlled and closed plastic flows, such as containers and fuel tanks, are less exposed to external contamination. Recyclates from municipal solid waste are usually more heterogenous and contain more contaminants (Juan et al., 2020).

3.1.3 Efficiency of waste management

The pipe industry is an important market for HDPE and investments in technology for sorting HDPE would be justified (Juan et al., 2020). To reproduce high quality plastics at low-cost advanced recycling management for solid waste has been developed (Al-Salem et al., 2009). Nguyen et al. (2020) found that factors such as the radius in which the waste materials are collected and delivered to a recovery facility can change the environmental impact of recycled HDPE. Thus, the efficiency within origin-to-destination transportation logistics need improvement (Nguyen et al., 2020). According to Alzerreca et al. (2015) the quality of the polymer can be affected during any of the recycling steps and Juan et al. (2020) point out the importance of improving these steps to achieve required pipe specifications. Improving the sorting and recycling process of plastic waste would lead to an increase of the allowed recycled PE content related to virgin HDPE materials in blends while fulfilling the requirements and specifications for PE80 and PE100 pipe grades, without compromising its performance (Juan et al., 2020). These results are similar to the ones reported by Al-Maaded et al. (2012) who mention that the method of handling, storage and processing of solid waste at the source plays an important role as it makes the recycling more efficient and brings economic benefits.

3.1.4 Quality of the waste

Different pipe grades are used for different applications, PE100 pipe grade for example is of high quality and fulfills the requirements of pressure pipes (Juan et al., 2020). The designations PE80 and PE100 are based on the long-term strength of the materials, the minimum required strength (Istrate et al., 2021). As previously mentioned, waste from households generally contain more impurities than industrial waste (Istrate et al., (2021). In households plastic waste is often mixed with other types of garbage which according to Al-Maaded et al. (2012) makes the separation process difficult. According to Istrate et al. (2021) the LCA results are highly affected by the recycled content of the blend. Using pure HDPE waste feedstocks, such as automobile fuel tanks and industrial containers, allows a higher recycled content to manufacture PE80 quality which results in a lower impact. Both Istrate et al. (2021) and Beheshtian Ardakani et al. (2018) mention that the source of the plastic waste affects the possibility to recycle the plastic and the quality of the recycled plastic. Post-consumer plastic waste such as crates/caps and packaging/detergency bottles usually originate from the waste stream collected from households while post-industrial containers and automobile fuel tanks can be obtained from industry and car scrapping etc (Istrate et al., 2021).

According to Istrate et al. (2021) PE80 pipe grade may allow a content between 5-96%. The large range is due to different sources of the plastic waste. For the manufacturing of PE80 pipe grades, plastic waste generated from crates and caps allow for a recycled content between 5-23% and packaging and detergency bottles allow for a recycled content between 9-37% (Istrate et al., 2021). However, plastic waste sourced from industrial containers allow for a recycled content of 25-68% and automobile fuel tanks for 31-96%. For pipe grade PE100 the maximum allowed recycled content is 31% when the source of the waste is automobile fuel tanks. Istrate et al. (2021) explain the lower percentage by the fact that PE100 grades are used in applications with higher requirements than PE80.

3.2 Positive effects of using recycled materials for pipe manufacturing

Table 4 Summary of positive effects
Summary of the positive effects of using recycled material in pipe applications that have been identified.

Positive effects of using recycled material	Explanation
Reduced use of resources and less energy consumption	The production of virgin HDPE requires oil and natural gas which will be reduced when producing recycled HDPE (Nguyen et al., 2020). Production of virgin HDPE is energy intensive and a higher recycled content reduces the energy consumption (Istrate et al., 2021).
Reduced microplastic pollution	By increasing the recycling, landfill disposal can be reduced and thereby microplastic pollution which is more likely to occur when plastic waste is disposed of in landfill. Recycling can also reduce the amount of plastic that reaches the ocean (Al-Maaded et al., 2012; Istrate et al., 2021).
More space due to reduced space for landfill	By recycling plastic the space used for plastic waste in landfill can be reduced and used for other purposes (Al-Maaded et al., 2012).
Lower impact on acidification	The production of ethylene with virgin content largely contributes to acidification. Thus, higher recycled content in blends reduces the impact on acidification (Istrate et al., 2021).
Lower greenhouse gas emissions	Manufacturing with recycled material can reduce the greenhouse gas emissions during raw material extraction and production (Arena et al., 2003; Brown & Buranakarn, 2003; Perugini et al., 2005).
Price reduction	By recycling waste, manufacturers may be able to reduce the price of products (Beheshtian Ardakani et al., 2018).

3.2.1 Reduced use of resources and lower energy consumption

According to Beheshtian Ardakani et al. (2018) recycling of HDPE waste products reduces the environmental impact and minimizes the use of resources. Since plastics are composed mainly of non-renewable resources, petroleum, or natural gas, recycling old plastics will use much less energy than manufacturing it from virgin material (Al-Maaded et al., 2012). Similarly, Istrate et al. (2021) found that higher recycled content in PE80 and PE100 pipes results in lower impact on the depletion of fossil fuels. This is mainly due to the energy consumption while producing ethylene, the virgin content bears the largest burden.

3.2.2 Reduced microplastic pollution and reduced space for landfill

Perugini et al. (2005) mention that landfilling is not encouraged by policy and Istrate et al. (2021) mention the importance of utilizing the waste and found that avoiding incineration of waste in favor of landfilling can reduce the carbon footprint. However, Istrate et al. (2021) also state that increasing the landfilling of plastic rejects can result in other environmental problems such as microplastic pollution. By increasing the recycling, landfill disposal can be reduced and thereby microplastic pollution which is more likely to occur when plastic waste is disposed of in landfill. Recycling can also reduce the amount of plastic that reaches the ocean, releasing toxic chemicals during their decomposition process (Al-Maaded et al., 2012; Istrate et al. 2021). Additionally, increased recycling decreases waste disposal in landfill and helps the environment by reducing the amount of space used in a landfill for plastic products (Al-Maaded et al., 2012; Beheshtian Ardakani et al., 2018).

3.2.3 Lower impact on acidification

Simões et al. (2014) concluded that in the production phase the environmental impact is higher for manufacturing with recycled HDPE than with virgin HDPE. The exceptions are the impact categories respiratory organics and fossil fuels (Simões et al., 2014). Thus, the use of fossil fuels and emissions to air are minimized when using recycled HDPE and the consumption of fossil fuels during the production phase has a significant environmental impact. Additionally, Istrate et al. (2021) found that due to the production of ethylene the virgin content is the largest contributor to the impact on acidification and a higher recycled content in the blend results in a lower impact on acidification (Istrate et al., 2021).

3.2.4 Lower greenhouse gas emissions

Using recycled polymers instead of virgin plastics can also reduce the energy consumption and greenhouse gas emissions during raw material extraction and production (Arena et al., 2003; Brown & Buranakarn, 2003; Perugini et al., 2005). This is further exemplified by Nguyen et al. (2020) that states that due to the consumption of energy to produce ethylene from oil and natural gas, the average greenhouse gas emissions for the manufacturing of 1 kg of virgin HDPE resin (cradle-to-gate) is higher than the manufacturing of recycled HDPE.

3.2.2 Reduced price of the final product

Manufacturers may be able to reduce the price of products by recycling waste products (Beheshtian Ardakani et al., 2018). In the production costs, energy makes up a larger portion than materials for recycled HDPE (Nguyen et al., 2020). According to Nguyen et al. (2020) this is mainly due to the low cost of plastic waste and since virgin HDPE is a large contribution to the recycled blend the feedstock cost governs the cost of the production of recycled HDPE. Juan et al. (2020) argues that the use of recycled HDPE could help reduce costs and lower the environmental impact. Due to the lower cost of recycled HDPE, production with recycled HDPE has a 30% lower potential internal life cycle (LC) cost (Simões et al., 2014). Simões et al. (2014) points out that from an economic perspective, recycling is the best EoL option for products manufactured with virgin HDPE. However, the EoL scenario of incineration with energy recovery shows a marginally lower potential internal LC cost but a higher potential external LC cost (Simões et al., 2014). This is due to revenues generated from the sale of electricity which are offset by the higher emission costs (Simões et al., 2014).

4. Discussion

The aim of this thesis was to identify challenges of using recycled HDPE in pipe application and how different sources of post-consumer HDPE for pipe manufacturing affect the quality of the pipe. The results indicate that HDPE is an excellent material to use in the manufacturing of pressure pipes (Alzerreca et al., 2015; Beheshtian Ardakani et al., 2018; Istrate et al., 2021; Juan et al., 2020; Singh et al., 2017). However, the manufacturing of virgin HDPE has a negative impact on the environment since it is energy intensive and requires a significant amount of raw materials (Istrate et al., 2021; Nguyen et al., 2020). Several of the authors of the studies included in this thesis point out that recycling HDPE can reduce the amount of plastic waste in landfills and conserve resources. Although, the results also suggest that there are several challenges of incorporating recycled HDPE in plastic pipes which will be further discussed in this section of the thesis. In the following discussion the results of this thesis are analyzed to highlight the challenges of using recycled plastic in pipe applications.

4.1 Properties

The findings of this thesis suggest that a main challenge to utilize recycled material from many different waste streams in plastic pipe manufacturing is how to maintain product performance and durability. Pressure pipes have unique properties and specific requirements such as service lifetime and the mechanical properties of HDPE, such as tensile strength and elongation at break can be influenced by the addition of recycled HDPE (Alzerreca et al., 2015). In general, the more recycled HDPE that is added, the lower the mechanical properties of the resulting blend. The results suggest that a possible explanation for the lower mechanical properties is that recycled HDPE may contain impurities or other degradation products that may weaken the material. Recycling processes can affect properties of pipes since it can cause chain scission, branching and cross linking (Juan et al., 2020). Additionally, crystallinity, which is affected by degradation, influences properties such as stiffness (Juan et al., 2020). However, the results suggest that properties such as tensile strength at yield, elongation at break and flexural modulus can be met even when using recycled material in the blend for producing plastic pipes (Juan et al., 2020). Thomas et al. (2015) collected a dozen samples of corrugated HDPE pipes in North America, South America, and the United Kingdom to evaluate if the samples met requirements of the pipes. The results showed that only two of the twelve samples met all the requirements. Five of the samples contained significant amounts of polypropylene which according to Thomas et al. (2015) is an indication of recycled HDPE being present. These results create concern that pipes that the studies included in this thesis have evaluated may also have contained a certain amount of recycled HDPE which can affect the result of allowed recycled content. Thus, further research of pipes where the initial composition is evaluated as a first stage is needed. Thereby, the result of allowed recycled content based on property requirements will have a higher credibility.

4.2 Contaminants of HDPE and additives to reduce the effect of properties

The result indicates that pipes made from virgin HDPE are already at risk of leaching chemicals. Additionally, contaminants are added while washing, cleaning and purifying the material (Alzerreca et al., 2015; Juan et al., 2020). Taken together, these results indicate that recycled HDPE may contain higher levels of contaminants than virgin HDPE. Materials in contact with drinking water can release unwanted compounds which can impact odor and taste, cause microbial growth, or be toxic (Diera et al., 2023). Additionally, Diera et al. (2023) found several compounds in HDPE pipes. Approximately 25% of the detected compounds were oxygeneted phenolic species which are likely related to commonly used phenolic antioxidants. Added antioxidants can decompose into many products which can degrade further (Diera et al., (2023). Thus, not only do the compounds found in HDPE pipes impose a direct threat if they leak into the water or surrounding environments but also because the compounds can decompose into other products and degrade. These contaminants, compounds or other products may impose a threat to both humans and the environment. The result also indicates that thermal exposure seems to be one of the main influencing factors on the degradation of HDPE pipes which may lead to leaching of chemicals (Greene, 2014; Isaacson et al., 2020; Juan et al., 2020). These observations are important to consider when areas are exposed to higher temperatures. Examples of areas that might be affected by such temperatures are areas where wildfires occur. This is of relevance since the impact of climate change contributes to an increased incidence of wildfires (Naturvårdsverket, 2022).

The incorporation of additives such as nanoclay or antioxidants or natural fibers such as sisal and jute has been suggested as a possible solution to improve the quality of the blends with virgin and recycled HDPE (De Oliveira Sampaio & Pimentel Real, 2012; Juan et al., 2020; Nguyen et al., 2020). This solution must be interpreted with caution since it does not include information about the full life cycle of these additives. It may be of importance to investigate and compare the production of these additives to assure that they do not result in further exploitation of resources and energy consumption. For example, the results state that nanoclay production is intensive but to improve the polymer properties very small quantities are needed (Na et al., 2016; Nguyen et al., 2017). To further explore these options LCA might be a suitable tool. In relation to these results regarding additives, Thomas et al. (2015) found that some additives dramatically improve the resistance of HDPE to exposures. Such exposures may be UV exposure, but the presence of additives may affect the results of tests performed on the pipes (Thomas et al., 2015). This is something to take into consideration when performing tests on HDPE pipes. For example, Thomas et al. (2015) mention that in addition to recycled content, presence of fillers and the use of poor quality carbon black may affect tensile tests.

4.3 Waste management and cost savings

The results of this thesis suggest that the characteristics of thermoplastics allow treatment including heating and formation multiple times (Nguyen et al., 2020). However, the results also indicate that the molecular weight of the polymer and its mechanical properties can be reduced when polymers experience several thermal cycles (Greene, 2014). There would therefore seem to be a definite need for improving current, and developing new, recycling processes to achieve the best possible quality of the recycled material. It is likely that this can lead to a higher allowed recycled content in pressure pipes which will lead to less resource use and energy consumption. However, these improvements may not be possible to implement everywhere since it requires investments, specific competence, and right technology. Countries with greater economic conditions have more possibilities to invest in proper recycling methods that reduce emissions and will lead to further cost savings (Al-Salem et al., 2009). Although the cost of producing plastic from recycled material is lower than producing plastic from virgin material it may still be less expensive to produce virgin HDPE than recycled HDPE if capital for investing in recycling facilities and technologies is insufficient. This may lead to continuing or increased production of virgin HDPE in some regions which can result in further contamination of the environment. To implement legislation to avoid this outcome might lead to further inequality as some regions may have to reduce or cut their production which will result in less income. A reasonable approach to tackle this issue could be to support developing countries to effectively implement strategies and technologies for recycling. Additionally, this is aligned with what the United Nations state in the Paris Agreement - to support developing countries for effective implementation to allow for higher ambition in their actions (United Nations Framework Convention on

Climate Change [UNFCCC], 2016). Gu et al. (2020) found a high correlation between the recycled plastic price returns and the performance of plastic manufacturers which implies that companies could be using more recycled plastic. According to Gu et al. (2020) crude oil is a volatile commodity, and these observations may imply that the availability of oil can affect the demand for recycled plastics. Additionally, the demand of recycled materials could also influence the adaptation of new regulations, technologies and business models and thereby affect recycling practices and related environmental performance (Gu et al., 2020).

The results suggest that there are currently limitations to manufacture pressure pipes with recycled content. The Plastics Industry Pipe Association (2022) mentions that plastic pipes are manufactured using engineered polymer materials that are very stable and the majority of pipes are made from a single type of plastic. This design facilitates simple recycling and supports a circular economy. Taken together, the results of this thesis and the fact that the design of plastic pipes makes them suitable for recycling indicate that even though it may not be possible to manufacture plastic pipes with certain amounts of recycled content, it is likely that plastic pipes may be recycled at their EoL to be used in other types of products. Although this does not relate to the aim of this thesis, it is of relevance from a wider environmental perspective to reduce the amount of plastic waste, reduce the use of resources and enhance the circular economy.

4.4 The role of the origin of plastic waste

Post-consumer plastic such as crates/caps and packaging/detergency bottles are usually sourced from households and generally contain a higher level of impurities than post-industrial plastic that is sourced from industry and car scrapping etc (Istrate et al., 2021). The results show that these impurities affect the quality of the recycled HDPE and thus also the plastic pipes manufactured from the recycled HDPE. Additionally, while sorting recyclable HDPE waste, contaminants are added which may also affect the quality of the final product (Beheshtian Ardakani et al., 2018). However, improvements have been identified to enhance the quality of post-consumer recycled HDPE. Thomas et al. (2015) also addresses that contamination is a main concern regarding the use of recycled HDPE and states that it must be controlled to ensure consistent performance of the pipes.

The results show that a reduction of the amount of contaminants and improvements in the process for sorting and recycling may reduce the risk of degradation of the HDPE in plastic pipes which may lead to leaching of chemicals (Alzerreca et al., 2015; Isaacson et al. (2020)). Additionally, compounds generated during plastic pipe production or used pipes that are no longer useful due to quality issues or quality problems during production may be recycled directly within the pipe industry (Beheshtian Ardakani et al., 2015). This may be a solution to avoid the contamination that other types of plastic waste can contain. Another strategy suggested by Thomas (2011) is to include a specification on recycled materials which will allow pipe manufacturers to make appropriate blends while controlling their properties.

The Plastics Industry Pipe Association (PIPA) mentions that plastic used in pipes are very different to single-use plastics, such as flexible packaging. This type of packaging is composed of multiple polymers and incorporates other materials, such as aluminum foil. Thus, plastic packaging is difficult to separate and recycle (Plastics Industry Pipe Association, 2022). Recent research has also suggested that waste created when quality problems occur during pipe production or after use, the plastic can be collected and recycled immediately (Beheshtian Ardakani et al., 2018). In a report from PIPA it is mentioned that recycled plastic used in plastic pipes can come from post-consumer plastics e.g. from households or industrial facilities, pre-consumer plastics that are diverted from the waste stream during a manufacturing process or from unused products or from rework material where plastic scrap material is generated during the manufacturer's own production of pipes (Plastics Industry Pipe Association, 2022). In the report it is also suggested that the pipe industry should work together with the building and construction industry to implement initiatives to recover off-cuts and products at the end of installation. Thereby, plastic that is more fit for purpose in pipe applications can be recycled and reused in other pipes. Additionally, by reusing rework material to make new pipes less waste is generated, and less waste goes to landfill (Plastics Industry Pipe Association, 2022). Manufacturers that use their own rework material also ensure that the material has a known origin and is certified for use in pressure pipes (Plastics Industry Pipe Association, 2022). Taken together, these points suggest that there is a great supply of waste from used plastic pipes in some areas to be used for recycling which could be blended with waste from plastic pipes collected during production. It is possible that these blends would have a better chance of being suitable for pipe applications while fulfilling the requirements. Although this type of waste may be more suitable for pipe applications it may require transportation of waste over unknown distances, and it is therefore important to analyze and quantify emissions to ensure that it does not adversely affect the environment to a greater extent than other options. Although initial observations suggest that there may be a substantial supply of waste from plastic pipes, in the report from PIPA two aspects that may contradict these facts are mentioned. First, that currently there is a low volume of material available for recycling. However, the industry is proactively capturing this material. Additionally, they discuss the fact that the service lifetime of pipes is relatively long which first of all means that plastic pipes do not contribute to the data of yearly generation of waste. Secondly, this means that the availability of plastic waste generated from plastic pipes may be low, which reduces the amount of plastic waste that can be recycled more easily for pipe applications. This increases the importance of developing strategies to enhance the separation of different types of waste which may benefit and facilitate the development of recycling in a more efficient way.

4.5 Recycled content in the blend

Research suggests that the allowed recycled content in the blend for plastic pipe manufacturing depends on the origin of the plastic waste and what type of pipe that is being manufactured. For example, the results suggest that the allowed recycled content differs for the pipe grades PE80 and PE100 (Istrate et al., 2021). PE80 pipe grades may allow a recycled content of up to 96% and PE100 pipe grades up to 31% (Istrate et al., 2021). These pipe grades can usually be used with the same functionality for certain applications (Istrate et al., 2021). Thus, it is important to note that the percentage of recycled content in plastic pipes varies depending on the pipe grade. Additionally, it is important to consider factors such as durability and other requirements in addition to the recycled content. Also, the specific application of the pipe and the origin of the waste also affects the recycled content. Taken together, the results of this thesis suggest that using pure feedstocks creates better opportunities for HDPE recycling in pipe applications. Industrial waste, for example, allows for a higher recycled content than municipal solid waste or waste from households such as packaging or detergency bottles (Al-Maaded et al., 2012; Istrate et al., 2021; Juan et al., 2020). The results do not rule out the influence of other factors but there would seem to be a need for improving the sorting and handling of plastic waste to simplify the recycling processes and be able to distribute the plastic waste for the right application at an early stage. The results also show that the presence of other types of plastic in the blend may deteriorate miscibility and decrease the possibilities of using recycled content in the blend. It is evident that the recycled content is of great variation ranging from 0 - 96% depending on the source of the plastic waste and the desired quality of the resultant plastic, which is related to its application domain. However, the results bring hope that future improvements may allow for incorporating more recycled material and increasing the recycled content. Additionally, the focus of this thesis was pressure pipes, mainly high pressure ones, but it may already be possible to use a higher recycled content in other types. The observation that PE80 pipe grades allow a higher recycled content than PE100 grades would seem to suggest that low-pressure pipes or non-pressure pipes may fulfill requirements with a higher recycled content. PIPA confirms this by stating that non-pressure pipes have greater flexibility to accommodate all forms of recycled materials and can incorporate recycled materials without compromising performance. They point out that there is capacity to increase the use of recycled material across a range of non-pressure pipes if suitable waste stream volumes are available. According to Thomas & Cuttino (2011) pipes containing 100% recycled PE can be manufactured to exceed the requirements for highway applications and have estimated service lifetimes of more than 100 years. However, Thomas (2011) mentions that recycled resins should only be used in low-risk applications or by experts who truly comprehend the limits involved with using recycled PE.

4.6 Future research

This study has shown that the quality of a plastic pipe containing recycled HDPE depends on several factors such as the quality of the recycled material and the quantity of recycled content. Previous research also concludes that it is of great importance to carefully consider these factors in the design and the production phase to ensure that required specifications are met. The use of recycled HDPE in pipe applications is an area that requires ongoing research and development to improve effectiveness of recycling processes as well as to meet short- and long-term goals for sustainability. Because of the restricted use of recycled material today it is of great importance to modify current standards and develop new potential recycled materials that demonstrate durability and fill the requirements for pipe application. In the future, initiatives may force virgin material to be replaced or partly replaced by recycled material in the production of pipes which is yet another reason why it is important to further study the possibilities of using recycled material in pipe applications.

Research should strive to explore new methods for removing contaminants in post-consumer plastic products to improve the quality of the recycled HDPE. New methods that simplify the monitoring and controlling of the quality of the recycled materials can be developed. Additionally, the process of recycling HDPE for plastic pipes involves a range of different steps. Research could focus on improving the efficiency and effectiveness of these steps, such as shredding, grinding and washing. Apart from removing contaminants, the addition of additives to the blend to improve the properties of pipes with recycled content should also be further investigated.

To understand the environmental impacts of recycled HDPE in pipe applications requires assessments of the full manufacturing process. Thus, it is important that research explore the life cycle of the material to identify opportunities for improving environmental performance. To augment the use of plastic waste for recycling it would be beneficial to further study strategies that facilitate the separation of waste. It may also be of interest to already in the initial phase design products in a way that makes separation easier.

As mentioned previously it is important to change regulations or apply incentives to increase the recycled content in pressure pipes as an important step towards more sustainable plastic production and use. Research of the possibilities to use recycled HDPE in pipe applications can increase the recycling rate of and contribute to a more sustainable and circular economy for this type of plastic.

5. Conclusions

Recycled HDPE is currently not being used to manufacture high-pressure pipes. However, the results indicate that there are possibilities of doing so with increasing knowledge and developed processes for recycling and blending. The possibilities to manufacture pipes from recycled plastic depend on various aspects, such as:

- Available resources and the quality of the recycled material.
- The origin of plastic waste which affects the quality of the recycled material.
- Current standards for manufacturing which are expected to be revised in the near future.
- Possibilities to maintain product performance and durability.
- The quantity of recycled content allowed in the blends. Currently, higher recycled content results in lower mechanical properties of the blend.
- Present additives and contaminants which can be a barrier for recycling, but some additives may increase performance of the blend. Additionally, chemicals can leach into, and affect, surrounding environments.
- The sorting and collection of plastic waste, which plays an important role to make the recycling more efficient and thereby minimize the risk of leaching chemicals as well as bringing economic benefits.

To address plastic waste problems, recycling is an important step towards environmental protection. Additionally, creating possibilities to increase the recycled content in plastic pipes will lead to lower energy consumption and use of resources. Mechanical recycling also causes relatively less pollution and needs low investment. To preserve the environment while meeting consumption demands, a global effort to shift the linear economy into a circular model must be made. Finally, continuing research and development of more efficient recycling processes will help tackle the challenges around using recycled material in plastic pipes.

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Lunds universitet

Miljövetenskaplig utbildning
Centrum för miljö- och klimatforskning
Ekologihuset
223 62 Lund