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Research Paper

Carbon footprint of monomer recycling for mixed synthetic textiles – a grave-to-gate analysis

Alina Ridderstad Nordberg [a], Greg Peters [a,*], Erik Klint [c], Efstathios Reppas-Chrysovitsinos [d], Anna Edsberger [b]

[a] Division of Environmental Systems Analysis, Department of Environmental and Energy Sciences, Chalmers University of Technology, Vera Sandbergs Alle 8, 41296 Gothenburg, Sweden
[b] Department of Sustainable Material Systems, Division of Materials and Production, RISE Research Institutes of Sweden, Box 104, 43122 Mölndal, Sweden
[c] Norwegian Institute for Sustainability Research, Stadion 4, 1671 Kråkerøy, Norway
[d] IVL Swedish Environmental Research Institute, Box 530 21, SE-400 14 Gothenburg, Sweden

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ABSTRACT

The production of textiles is increasing globally, generating large volumes of mixed textile waste. Research on innovative ways to treat this waste is expanding but there is a lack of published environmental assessments of methods for recycling the common synthetic fibre blend of polyethylene terephthalate (PET) and elastane. We analyse glycolytic depolymerisation processes using life cycle assessment to evaluate the climate benefits in comparison to business-as-usual (BAU). Two recycling scenarios are compared – one targets both PET and elastane (scenario A), the other only recycles PET (scenario B). These scenarios were developed in a laboratory environment and then scaled up *in silico*. The functional unit was the treatment of 285 tonnes of PET-elastane textile waste per year. The life cycle inventory was modelled using LCA for Experts version 10.9.3.0 and ecoinvent 3.11. Using the EF3.1 factors for life cycle impact assessment, the total climate burden of the two studied scenarios was around 1600 and 2200 tonnes of CO_2-eq, respectively. This means the emissions of the recycling cases exceed their respective BAU cases by around 62 and 98% respectively. While some additional economies of scale may be possible beyond those for which we have already accounted, and there may be strategic reasons to pursue polymer independence in a deglobalizing world, this study represents a case that contradicts the idea that recycling will solve the environmental problems of fast fashion.

1. Introduction

Global textile production continues to increase primarily to satisfy the apparel industry (NCC, 2018). Textile complexity can arise from several product features, including fibre composition, dyes and chemical finishes, and attached or printed components. In particular, fibre complexity, i.e., number and types of fibres used and the diversity of their combinations, is also increasing as a result of i) market competition for designing and patenting blending "recipes" (Wang and Cheng, 2025), ii) economic incentives to mix fibres with lower-priced materials (El-Moursy et al., 2024), and iii) an effort to optimise or innovate textile functionality (Das et al., 2021). This accelerated production of increasingly complex textile products challenges environmental sustainability by demanding significant natural resources, emitting various greenhouse gases and other contaminants, and putting pressure on current waste management practices such as incineration and landfilling (Bartl, 2020; Bianchi et al., 2023; Niinimäki et al., 2020).

Consequently, new and emerging textile recycling technologies are being explored to respond to national and international calls for more sustainable and circular textile production and textile waste management practices (Sheng et al, 2026). Some researchers have focussed on the challenge of recycling garments composed of blended fibres (Choudhury et al., 2024). A case of increasing interest is the polyester/elastane blend. Polyethylene terephthalate (PET) is today the globally dominant polyester polymer, accounting for more than half of global fibre production by mass (The Fibre Year Consulting, 2022). Elastane, a

Abbreviations: PET, Polyethylene terephthalate; PU, Polyurethane; PTMG, Poly(tetramethylene ether) glycol; BHET, Bis(2-hydroxyethyl) terephthalate; DMSO, dimethyl sulfoxide; EG, Ethylene glycol; BAU, Business-as-usual.

* Corresponding author.
E-mail address: petersg@chalmers.se (G. Peters).

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synthetic polyurethane-urea type fibre also known as Spandex and Lycra, is extensively used in various blends with natural and/or other synthetic fibres when textile elasticity is considered an important functionality, due to its capacity for highly reversible extension. Polyester/elastane blends are used extensively in sportswear, leisurewear, underwear and outdoor clothing due to the combination of breathability and elasticity. We focus on sportswear in this article, which has a relatively high proportion of elastane.

Textile recycling systems are most clearly described by the degree of structure retained during recycling, e.g.: fabric recycling; fibre recycling; polymer recycling or monomer recycling (Sandin and Peters, 2018) so we use that nomenclature for overarching systems here. This reflects the fact that for example what people might call "chemical recycling" typically requires several mechanical unit operations or processes. Polymer and monomer recycling systems use chemical processes such as depolymerisation, solvolysis, ionic liquid dissolution, alkali digestion and pyrolysis. These have the potential to not only reduce environmental impacts but also recover valuable molecular structures and allow fibres to be rebuilt for new textiles, in good alignment with circular economy principles and goals (Bianchi et al., 2023; Rickert et al., 2020).

Industrially, PET is produced from terephthalic acid (TPA) and ethylene glycol (EG) in a polymerisation process. PET can be depolymerised back into its monomers by one of several solvolysis methods, i.e. glycolysis, hydrolysis and alcoholysis. Subsequently, the produced monomers can be repolymerised back into PET for fibre spinning (Xin et al., 2021).

Elastane, on the other hand, is not a distinctively defined molecule, but rather a family of polymeric molecules, a polyurethane-urea type polymer consisting primarily of two alternating building blocks, an aromatic diisocyanate and a polyol. The elasticity of all elastanes is caused by connecting hard and rigid segments formed by aromatic isocyanates with soft extendable segments of a polyol (Boschmeier et al., 2023a). Many different types of polyols can be used to build polyurethanes, but in elastane the polyol (indicated by the orange box in Fig. 1) is typically a polyether called polytetramethylene ether glycol (PTMEG). Additionally, chain extenders, typically diamines, are used to impart specific functionalities to elastane. The specific chemistry of these chain extenders varies between grades and producers. Depolymerisation of elastane might generate 4′4 methylene dianiline (MDA), an aromatic amine which is a common degradation product from the hard segments. MDA is toxic to humans and aquatic life, being a carcinogen, a potential mutagen and categorised as a substance of very high concern (SVHC) by the European Union. MDA is a valuable chemical if it can be isolated and purified, however its uncontrolled release should be prevented.

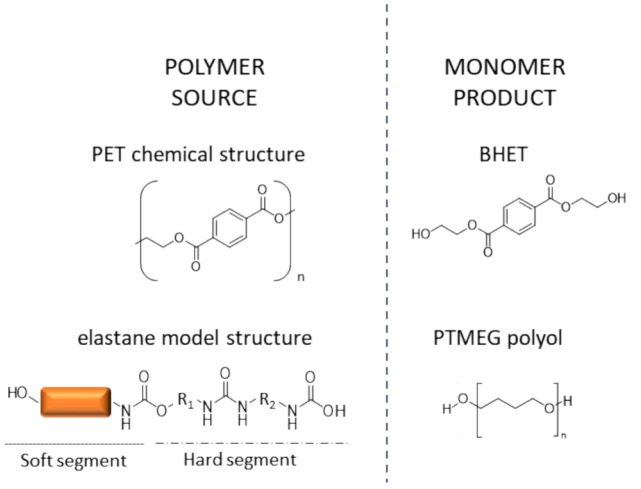

Fig. 1. Key relevant structures in the recycling of PE-PU blended fibre. The orange box represents a polyol component in the elastane, while R_1 and R_2 are different, often aromatic hydrocarbon units. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In this study, simultaneous depolymerisation of PET and elastane is realised by solvolysis in EG catalysed by potassium acetate (KOAc). In the case of polyester, the glycolysis produces BHET by cleavage of ester bonds and addition of EG in a 1:1 ratio. For elastane, the polymeric chain is broken at the conjunction between the hard and the soft segments. The product is the soft segment polyol PTMEG, which accounts for about 70% of the elastane polymer by weight, while the residues from the hard segments are discarded.

Systems for closed-loop recycling are only beginning to emerge, and most research is focussed on pure waste streams rather than blends, while research on recycling blended fibres has focused on recovering cotton and polyester (Dissanayake and Weerasinghe, 2021). Patents for PET and PU depolymerisation processes were reported as early as the 1940s (Scheirs, 1998), only a few years after the first patents for the polymerisation of these materials, indicating that, although chemical recycling has been contemplated for nearly a century, industrial development of such processes faces significant barriers (Xin et al., 2021). Despite the existence of processes to recycle PET (Damayanti and Wu, 2021) and polyurethane (Simón et al., 2018) as single materials, blended textiles are typically harder to recycle (Choudhury et al., 2024). In particular, the presence of elastane in blends is known to further complicate the recycling process (Bianchi et al., 2023). An examination of the literature indicated that there is currently only one study specifically focused on investigating the chemical recycling of blended polyester/ elastane textiles (Xu et al., 2022) while four other studies explored the potential for selective dissolution of elastane from blended textiles (Boschmeier et al., 2023b; Vonbrül et al., (2024); Phan et al., 2023; Wang et al., 2022).

Recycling technologies need to be prospectively assessed against established waste management practices from a lifecycle perspective to optimise the processes before they are scaled up, identify their relative advantages and limitations, and anticipate their environmental impacts (Thonemann et al, 2020). Such comparative assessments can inform practitioners, policymakers, and researchers on the potential integration of different recycling technologies into existing urban waste management systems. Life cycle assessment is an ISO-standardised procedure ideally suited to this task (International Organization for Standardization, 2006a, 2006b). Typically, it involves drawing a boundary around a product or process, estimating the total flows across that boundary of energy, materials and pollutants, and using simplified assessment models to aggregate the impacts of those flows on the environment. Previous LCAs of textile recycling routes have explored various aspects in a Scandinavian context and Sweden is a country of interest - a national regulation took effect in 2025 that prohibits the disposal of textile waste into municipal solid waste, a stream that is typically incinerated for energy recovery (Schmitz et al, 2024). The regulation (SFS 2023:908) placed responsibility on local governments to collect the waste separately, which may be expected to significantly increase the potential for textile recycling. Previous LCA work relevant to this context includes a comparison of textile reuse, incineration and polymer recycling in Sweden using the IPCC's 2007 characterisation factors (Zamani et al., 2015). It suggested there were benefits in recycling but greater benefits in reusing textiles. A subsequent review of various LCA studies of reuse and recycling confirmed this relativity and pointed out circumstances under which recycling was not advantageous (Sandin and Peters, 2018). A Swedish LCA comparing recycling mixed cotton and polyester textile waste with incineration considered seven different environmental indicators (mostly taken from the European Union's original 2018 EF method) and showed that recycling was beneficial for water conservation on account of avoided cotton production, but the benefits of recycling were more ambiguous for the other indicators like climate change (Peters et al., 2019). Phan et al (2023) performed an LCA on the selective extraction of PET from PU-containing fabric but did not

consider the recovery of polyols from the PU. They also assumed that recovered PET fibres can be melt-spun in a closed loop, although on account of contaminants and lost molecular weight in postconsumer textiles, in practice meltspinning only happens with bottle PET.

There is a lack of studies examining the potential to recycle monomers in mixed PET/PU sportswear waste using LCA. Meanwhile, great hope is held for textile recycling among policymakers and fashion retailers to make present consumption patterns sustainable, apparently based on general ideas rather than specific information. The present study aims to examine the reasonableness of that hope in a specific case where a research gap exists, namely PET/PU blended textiles, by using new laboratory empirical work and the latest life cycle impact assessment method for climate change. The goal of the study is to inform policy makers and process designers on climate change impacts of mixed textile waste recycling to foster informed decisions that will benefit sustainable waste treatment of textiles in the EU. This goal is pursued by developing a life cycle perspective on a proposed process and evaluating whether the process is climate-friendly in comparison to business-as-usual (BAU).

2. Materials and methods

2.1. LCA scope definition

The study is based on a grave-to-gate LCA. The scope is based on the treatment of elastane-rich post-consumer sportswear, for which no publicly available data on the scale of the waste stream is available. Via personal communication with major sportswear retail companies in Sweden we established an estimated total annual flow of ~950 tonnes of elastane-rich blended polyester/elastane (80/20) through the national economy. 30% of this flow would be large enough to provide a steady material flow for a small industrial facility and adequate as a basis to test upscaling processes prior to establishing a larger industrial facility, possibly with a Scandinavian or international catchment. The functional unit of this LCA is therefore the treatment of ~285 tonnes of polyester/elastane textiles in Sweden. Sweden was chosen as the geographical setting for our study as this is a location with legislative drivers and an existing research focus on textile waste treatment, making it interesting as a setting for the development of the recycling facility. However, it is still placed in the context of the EU waste treatment norms, because of the economic structures and policies around waste treatment that exist on this level. The geographical setting is reflected for example in the selection of energy data and transport distances, with most tradeable commodity data based on European averages (e.g. solvent supplies).

As will be further described in the next section, data for the flows and yields was taken from primary laboratory results, while background data for the system and its emissions was mostly taken from datasets within the tool LCA for Experts version 10.9.3.0 (Sphera, 2025) and the ecoinvent 3.11 database (Ecoinvent, 2025). The laboratory data is based on depolymerisation experiments at the gram scale. To prospectively assess this, scale-up is based on maintaining reaction stoichiometry but considering the efficiency of industrial scale equipment and the addition of recycling measures that are irrelevant at bench scale.

The impacts from the assessed systems were calculated using the characterisation factors for climate change in the EF 3.1 package (European Commission, 2025). The decision to focus on climate as impact category was made because the increased use of energy and chemicals in recycling systems are expected to have additional climate impacts in comparison to BAU. Moreover, since the textile industry is causing a large share of global greenhouse gas emissions (Peters et al, 2021), a focus on climate and the potential to decrease climate impact through recycling is of interest for many stakeholders within the textile supply chain, such as process developers and policy makers.

2.2. Life cycle inventory modelling

The textile waste in focus is a post-consumer flow consisting of PET and elastane fibres mixed in a mass ratio of 80/20. Elastane is the minority fibre in PET/elastane blends and ranges between 1–30% in different garments with an average content of 7% (Refashion, 2023). Therefore, the modelled feed is in the higher end of this range. For simplicity, the focus lies on analysing the impacts of the recycling procedure for these materials with monomers as products, and not the subsequent fibre production, since that lifecycle phase will look the same regardless of how the monomers are produced. More specifically, the study aims to assess three scenarios for how these precursors for synthetic textile fibres can be produced, and their waste treated. The three scenarios are:

- Scenario A: Recycling mixed PET and elastane textile waste into new PET and elastane monomers with the potential for use in the production of textile fibre and new clothing. A glycolysis process is applied to the fibre mixture in order to depolymerise both synthetic fibres in the same reactor.
- Scenario B: Recycling mixed PET and elastane textile waste into new PET monomers that could go into textile fibre production and become new clothing. Elastane is initially separated for disposal from the mixed waste stream prior to a glycolysis process for depolymerisation and recovery of PET monomers.
- Scenario C: A BAU case in which the textile waste consisting of PET and elastane is incinerated for energy recovery after a use phase, and the monomers are produced from virgin material, i.e. crude oil.

An overview of the three scenarios investigated is presented as flowcharts in Figs. 2, 3 and 4. More detailed figures are provided as Fig. S1 and S2 in the Supporting Information. In all flowcharts, different unit operations in the system are given different colours to distinguish between the different process steps. The colour code can be followed through to the later presented results. In both recycling scenarios the first steps include collection and pre-treatment to prepare the textile waste for depolymerisation.

2.2.1. Pretreatment

In the model, general textile waste is gathered from users at the three major conurbations within Sweden (Stockholm, Gothenburg and Malmö) for sorting to produce various recyclable streams including an elastane-rich PET stream. That relatively small stream is then transported to a central recycling facility in Gothenburg, the country's major industrial port city. Transport and sorting within each conurbation was excluded because the transport would be shared with the much more massive total textile waste stream, urban distances are short compared to inter-city transport, and sorting equipment has very low impacts in comparison with the rest of the system (Lidfeldt et al 2022). On the other hand, inter-city transport was included using an average distance of 334 km which was estimated based on the relative populations in those cities and their distance to Gothenburg. At the facility, the textile waste passes through an industrial-scale cutter then two shredders (based on the 7.5 kW NSX-QD350, the 2.6 kW NSX-FS1040 and 6.6 kW NSX-QT310 machines, all from New Shun Xing) consistent with the work by for example Jonsson and Vuorinen (2016) and Lindström et al (2020). The material is also washed to eliminate contaminants using an industrial-scale continuous washer (CLM, 2026).

2.2.2. Combined glycolysis

As shown in Fig. 2, in Scenario A the main idea is to depolymerise both polymers in a conjoint glycolysis process, where the solvent ethylene glycol (4.9 kg per kg waste textile) and the catalyst potassium acetate (0.02 kg per kg waste textile) are added to a stirred tank batch reactor which is operated at 200 °C for 2 h, based on Doifode (2023). In the industrial scale model, this is based on a 4 m^3 reactor (Li and Li,

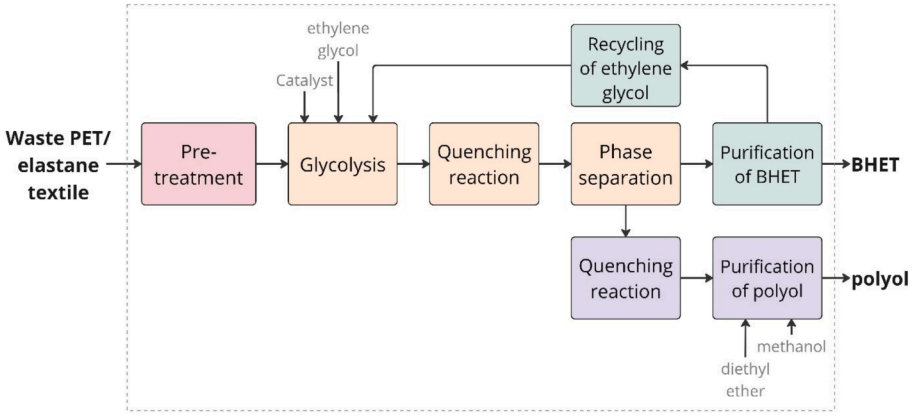

Fig. 2. Flowchart showing Scenario A, where the textile waste is recycled into the monomers BHET and polyol.

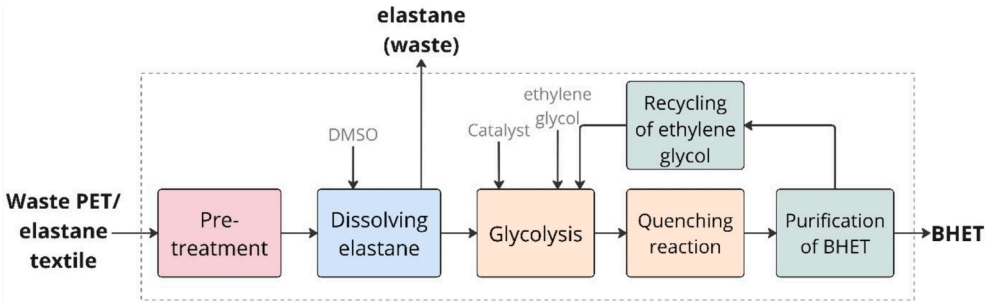

Fig. 3. Flowchart showing Scenario B, recycling of the textile waste into BHET monomers and elastane waste.

2025) with heating and agitation energy estimates for this scale based on the scale-up principles of Piccinno et al (2016). Potassium acetate is produced by reaction of acetic acid and potassium hydroxide, but LCI data for producing the latter was not available in Ecoinvent. Therefore, this was approximated by using an electrolysis process for producing sodium hydroxide, subtracting the impacts for production of sodium chloride and adding impacts of a molar equivalent potassium chloride input. After the depolymerisation products are cooled and quenched with water, the monomers are separated in an industrial three-phase centrifugal separator (IHI, 2025).

2.2.3. *BHET purification*

The flow containing the monomer BHET is purified using a sequence of filtration and crystallisation steps. Initial filtration at 75 °C enables solid impurities and PET that was not fully depolymerised to be separated and discarded. Subsequent filtration in a filter press at 4 °C driven by a 4 kW pump (Autemi, 2025) allows crystals of pure BHET to be removed from the glycol solvent with a yield over the whole system of 65% by mass (Doifode, 2023). (This is the mass of BHET product in relation to the mass of PET that enters the system.) Cooling operations were assumed to be delivered with an industrial chiller with a typical coefficient of performance of 3 (DNV, 2022). At scale, it is assumed to be economically necessary to recycle the ethylene glycol solvent. A previous LCA of an industrial-scale glycol purification system using activated carbon and distillation (Olsson, 2018) was used to model this step.

2.2.4. *Polyol purification*

The monomer polyether polyol from the elastane fibre is purified by two sequential purification steps in accordance with Doifode (2023). In the first, polar contaminants are removed using a (70:30) methanol/water solvent to disperse the polyol at 5 °C. Centrifugation in a 5.5 kW centrifuge (IHI, 2025) is employed to remove heavy and dissolved contaminants with the liquid phase and the water is discharged to wastewater treatment while 97% of the methanol is recovered by distillation. Subsequently, light non-polar contaminants are removed after dissolution of the polyol in diethyl ether with 100 mg/kg ferrous sulfate added to inhibit peroxide formation. The solvent is recovered by boiling and condensation. This leaves the polyether polyol as a clean product with an overall yield of 55% by mass, which is the amount of polyol monomer product in relation to the amount of elastane that enters the system. The different outflows of chemicals and contaminated water are treated in a hazardous waste treatment facility on account of possible MDA-contamination, and water that is not contaminated is managed in a municipal wastewater facility, with all processes taking place in Sweden.

2.2.5. *Dissolving elastane*

In scenario B, we view elastane as a contaminant to be removed from the polyester flow. The pretreatment step is the same as for scenario A, but the polymers in the material are instead separated before the depolymerisation as can be seen in Fig. 3. Elastane is removed by adding dimethyl sulfoxide (DMSO) to the textile -in a mass ratio of 20:1 to dissolve elastane. The temperature is maintained at 120 °C for 30 min. Full scale energy consumption is estimated in accordance with Piccinno et al (2016). After the liquid is drained from the reactor the solid polyester remaining is washed with additional DMSO. The DMSO is recycled after distillation at 189 °C, leaving elastane as a solid residue. The polyester is washed with water to remove any DMSO remaining and the solids are dried.

2.2.6. *PET glycolysis*

This process is similar to the glycolysis described previously, but has been optimised for the recovery of PET instead of aiming for both PET and polyol recovery. The polyester flow is depolymerised through a glycolysis process where ethylene glycol is added as a solvent (5 kg per kg polyester), and aluminium magnesium oxide is added as a catalyst

(0.5 g per kg polyester). The reactor is operated at 230 °C for 60 min. BHET monomers that leave as products from the depolymerisation are then purified in the same manner as the purification of BHET in scenario A, arriving at a yield over the whole system of 106% by mass, corresponding to a molar yield of 80%, that is the amount of BHET product in relation to the amount of PET entering the system (Guo et al, 2021). (The yield is above 100% by mass because BHET has a higher molecular weight than the repeating unit of PET, consuming 1 mol of EG per mole BHET produced.) The choice of catalyst is different to the one used in scenario A because aluminium magnesium oxide which is more effective in depolymerising PET compared to KOAc, used to catalyse scenario A, where a compromise between catalytic activity towards PET and elastane had to be made. The ethylene glycol solvent is purified and recirculated back into the system as per scenario A.

2.2.7. Business as usual

The BAU-scenario for the recycling scenario A is shown in Fig. 4. The BAU modelling includes two parts of the lifecycle: the production of the monomers BHET and polyols; and the waste treatment through incineration with energy recovery. One BAU scenario per recycling scenario is modelled, as the number of products differs in the different scenarios. In scenario A, both polyester and elastane fibres are recycled into monomers, and thus the corresponding BAU scenario (C-A) needs to produce both monomers, for comparability reasons. In scenario B, only the polyester fibre is recycled into BHET monomers, and the corresponding BAU scenario (C-B) produces only BHET monomers. The flowchart for C-B would be exactly as per Fig. 4 but without the production of polyol and its raw materials.

The modelling of the BAU scenarios was based on stoichiometric reaction calculations, scaled up to the functional unit and modelled using existing background processes in LCA for Experts. For the case of BHET, the production is modelled through the production processes of the two ingredients EG and terephthalic acid using existing processes, while for the production of polyol monomers, an existing process for the direct monomer production was used. The incineration is modelled using a waste treatment process for incineration with data for Europe in general, and the energy it generates is included as avoided heat and electricity production extending the system to include electricity production and heat production in Sweden. This is appropriate since the incinerator would be located in Gothenburg and would displace Swedish energy supplies.

Since this is a prospective study built on a diversity of data sources, a simple approach was taken to uncertainty analysis. A principal source of uncertainty in the LCA results is the accuracy of the commercial database information. This was reflected in our analysis by using the square of the geometric standard deviation Ecoinvent associates with relevant incineration and chemical production life cycle inventory data. The consequences of this approach are discussed in the next section.

3. Results and discussion

3.1. Life cycle inventory results

Major material and energy flows for the foreground system are shown in Table 1 for each scenario (more detail is provided in Table S1 in the Supporting Information). Some observations regarding these results are the considerable differences between BHET production in scenarios A and B – in the latter it is 63% higher because this process is optimised for BHET production at the expense of producing no polyol product in comparison to scenario A. It is also noticeable that the electricity consumption is almost 5 times higher in scenario B, though as we shall see, this difference does not dominate the characterised results. The energy used by operating the recycling system is based on reported efficiencies of industrial equipment. At larger scales than this a process developer would probably investigate the potential for energy recovery in detail. In this model the process for recovery of ethylene glycol and various other heating steps might offer some potential for thermal integration. Being located in Sweden means that they are carbon efficient but at larger (e.g. international) scale, integration with other chemical engineering elements in the background system could theoretically offer additional savings, although at the cost of additional transportation impacts for the blended textile waste input.

As it is with the energy demands shown in Table 1, scaling up the material flows derived from laboratory work to the functional unit of ~285 tonnes of textile waste entering the system every year means scaling up experimental flows that may still have some room for optimisation. On the other hand, our analysis has taken into account the potential for recovery of solvents which are typically wasted in laboratory experiments. While the material flow data for scenarios A and B are based on laboratory experimental results scaled to the functional unit and adjusted to reflect full scale equipment, flows for scenarios C-A and C-B are based on full scale production data scaled to the product flows of scenarios A and B. This is of course not the first prospective life cycle assessment to grapple with systems at different technological readiness levels (e.g. Peters et al, 2019), but it is important to attempt such comparisons before the impacts of technology or policy decisions are locked in (Arvidsson et al, 2018) and the provision of life cycle inventory data (e.g. via supporting information) is one way to allow future readers to adapt LCA as new data emerges.

3.2. Climate impacts

Fig. 5 shows the total climate impact in terms of Global Warming Potential (GWP) expressed in tonnes of CO_2-eq per functional unit for scenarios A and B, organised as sequential groups of chemical processes that represent the key steps in each scenario. The total emissions of scenario A, in which we focus on recycling both the monomers, are 24%

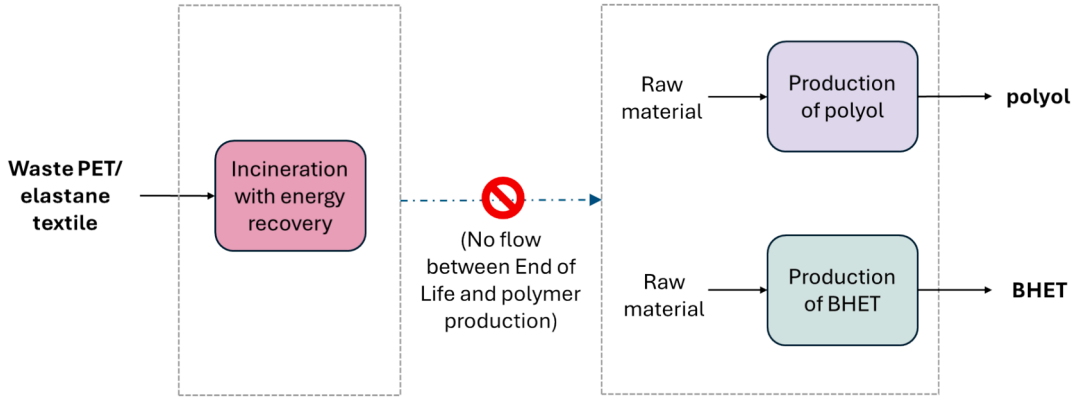

Fig. 4. Flowchart for scenario C-A: the BAU for treatment of the textile waste and production of monomers, including system boundaries inside dashed lines.

Table 1
Mass flows and energy flows in unit kg/yr and MJ/yr respectively, per functional unit for the three scenarios A, B and C where data for scenario C is given for when comparing BAU to scenario A and B.

Scenario	Inputs		Unit	Outputs		Unit
A	Textile waste	283,000	kg/yr	BHET monomer	147,000	kg/yr
	Detergent	3110	kg/yr	Polyol monomer	31,100	kg/yr
	EG	138,800	kg/yr			
	KOAc	5660	kg/yr			
	Methanol	44,511	kg/yr			
	Diethyl ether	8490	kg/yr			
	Ferrous sulphate	283	kg/yr			
	Water	4,265,000	kg/yr			
	Electricity	2,302,191	MJ/yr			
B	Textile waste	283,000	kg/yr	BHET monomer	240,000	kg/yr
	Detergent	3110	kg/yr	Elastane waste	56,600	kg/yr
	DMSO	67,900	kg/yr			
	EG	103,700	kg/yr			
	Mg-Al oxide	113	kg/yr			
	Water	5,260,000	kg/yr			
	Electricity	10,353,884	MJ/yr			
C-A	Textile waste	283,000	kg/yr	BHET monomer	147,000	kg/yr
	EG	71,900	kg/yr	Polyol monomer	31,100	kg/yr
	Terephthalic acid	96,200	kg/yr	Electricity	3290	MJ/yr
				Steam	5890	MJ/yr
C-B	Textile waste	283,000	kg/yr	BHET monomer	240,000	kg/yr
	EG	117,000	kg/yr	Electricity	3290	MJ/yr
	Terephthalic acid	157,000	kg/yr	Steam	5890	MJ/yr

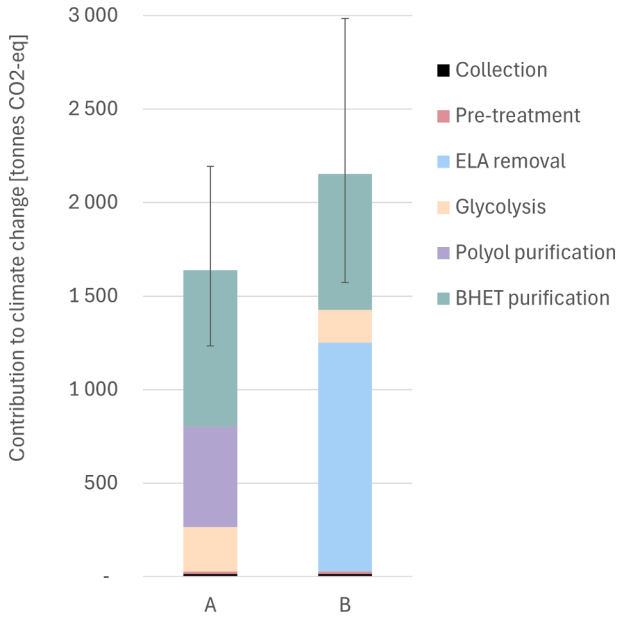

Fig. 5. Contributions to climate change by process step in the alternative scenarios.

lower than scenario B although the difference between them is smaller than the associated uncertainty margins. The BHET purification process is significant in both scenarios, causing 51 and 34% of the total contributions to climate change, respectively. Most of the impacts in scenario B are related to the elastane removal process (57%) while the polyol purification process contributes 33% of these emissions in scenario A. In both scenarios, carbon dioxide is the dominant greenhouse gas (96 and 93% of the total burdens, respectively).

One might have expected the simpler system (scenario B) to outperform the more complex alternative, but scenario B suffers in the comparison on account of the relatively high solvent addition requirement for the elastane dissolution using DMSO and the additional use of the solvent for washing the solid PET (see supporting information Fig. S2) combined with the relatively high climate impact of producing this solvent. While the climate impact of producing diethyl ether is relatively high compared to the other solvents (8.4 kg CO_2-e/kg diethyl ether) scenario A uses a relatively small mass of this (8 tonnes/year) compared to the use of DMSO in scenario B (68 tonnes/year) and the solvent has a considerable impact during production (3 kg CO_2-e/kg DMSO), itself approximately twice that of ethylene glycol 1.6 kg CO_2-e/kg) according to the Ecoinvent database (Ecoinvent, 2025).

This focus on the origins of the emissions is reflected in Fig. 6, which is organised on the basis of the types of emitting processes, rather than their sequence. Analysing the contributions to the total impact this way, it is noticeable that for the facility, "scope one" climate emissions (WRI, 2004) are non-existent, scope two is minimal, and waste management is responsible for a large part of the emissions in both recycling scenarios (46 and 33% in scenarios A and B, respectively). The treatment of wastewater and more significantly of hazardous organic wastes are the contributors here. These are distinct from the other major item, solvent recycling, which is 32 and 28% of the impacts of scenarios A and B, respectively. In both cases, this is mostly about recovering glycol after the BHET purification step. In both scenarios, direct (foreground system) electricity consumption (i.e. not in a solvent production or waste

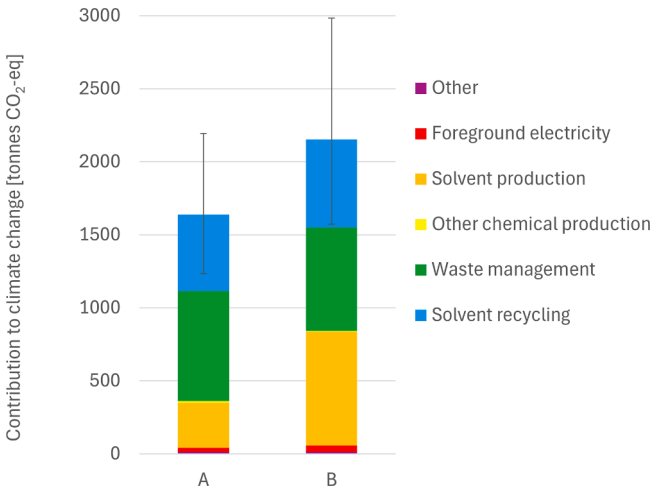

Fig. 6. Scenario performance by emission source.

management facility) stands for a minor part of the emissions, as do the pre-treatment steps. This of course becomes important for the process designer when designing the system, as it appears not to be the depolymerisation nor the washing and shredding of the textile waste that is the hotspot – instead the designer should focus on improving the subsequent purifying steps of the system.

Nevertheless, as is apparent from Fig. 7, significant economies of scale have been achieved in both scenarios by introducing solvent recycling (absent in the original laboratory process data) during the scale-up process. Recycling glycol, methanol and diethyl ether in scenario A and glycol and DMSO in scenario B result in a reduction in total impacts by an order of magnitude. Considering the small (2%) contribution made by foreground system electricity consumption in both scenarios, there is little potential for energy efficiency measures (e.g. pinch analysis) to significantly improve the carbon footprint, at least in a Swedish context where predominantly renewable energy and some nuclear power are responsible for low greenhouse emissions in the electricity sector. Sweden's electricity supply has the lowest carbon intensity among the supplies of all 27 nations in the EU (7 g/kWh – EEA, 2025). If the facility was built instead in Estonia, which is the opposite extreme within the EU (585 g/kWh – EEA, 2025) then foreground system electricity consumption would be the origin of 58% and 63% of the total greenhouse gas emissions for scenarios A and B respectively, and clearly worth further attention from a climate policy perspective.

In Fig. 8 the main processes contributing to the results for the BAU cases are displayed along with the total results for the relevant recycling cases. The results are similar for the two BAU cases. Both recycling scenarios perform worse than their respective BAU scenarios when studying climate change, with emissions 62% and 98% higher than BAU, although the error margins for the recycling and BAU cases overlap, suggesting that we should not consider them significantly worse than their BAU equivalent scenarios. It can be seen that Scenario A avoids the production of new polyols and 116 tonnes of CO_2-e shown as part of the BAU histograms in Fig. 8, but this is not enough to compensate for the 549 tonnes of CO_2-e shown in Fig. 5 that are emitted during polyol purification and driven by the associated demand for the solvent and the additional hazardous waste management. Furthermore, one can see in Fig. 8 that it is the incineration in the BAU cases that accounts for most of the GWP impact, even if the incineration includes energy recovery for heating and electricity purposes.

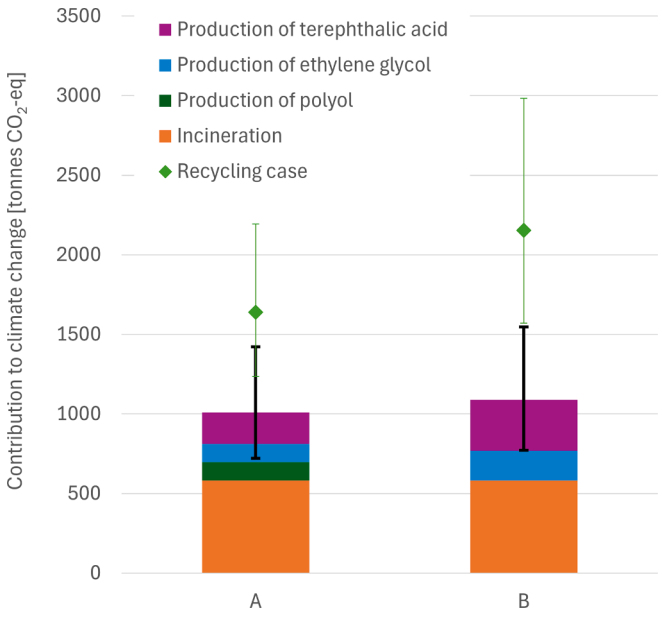

Fig. 8. Total impacts from each BAU scenario in tonnes of CO_2-eq per functional unit compared to their corresponding recycling scenarios.

3.3. *Other perspectives on elastane/polyester blend recycling*

The chemical recycling processes proposed here seem promising since they are not significantly worse than the current linear life cycle of

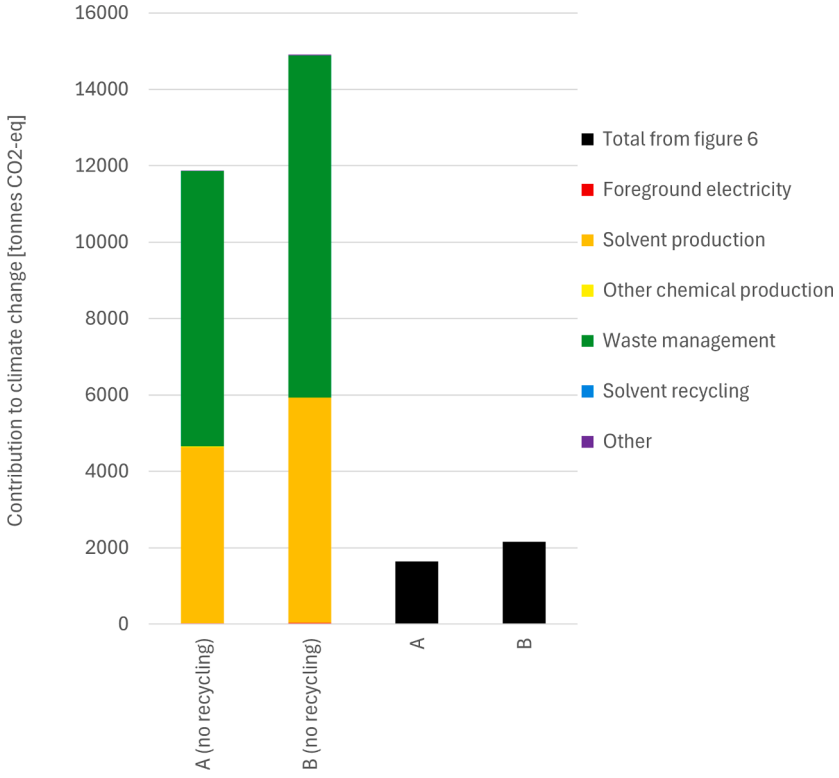

Fig. 7. Effect of adding recycling during scale-up.

elastane/polyester garments. Nevertheless, this outcome is in conflict with the fashion retail industry narrative that the pursuit of circularity will *reduce* carbon emissions (Howlett, 2023). It also brings into question whether present legislative efforts to forbid textile waste combustion and to increase recycling are appropriately tailored to the sustainability challenge. Even if garments are equipped with fibre content labels that survive their domestic use (e.g. stating "10% elastane") the detailed monomeric constituents of the textiles are not disclosed to the customer nor to the waste management facilities. While in contrast to this study, some previous studies have shown mixed textile waste recycling offers environmental benefits, they do not always consider process feasibility in great detail. For example, the LCA by Zamani et al (2015) showed that using a separation process based on N-methylmopholine-N-oxide (NMMO) to recycle mixed cotton/polyester waste created overall climate benefits, but the cost and instability of this chemical has driven researchers to look for more practical processes based on cheaper chemistry. This was the background to Peters et al. (2019) in which mixed cotton/polyester waste was separated using alkaline hydrolysis. That more detailed analysis of the unit operations showed the potential for climate benefits from recycling, but these were small in comparison to the uncertainties. The assessment of recycling by Phan et al (2023) was climate-positive, but the potential to melt-spin post-consumer polyester polymer on which it was based has not been demonstrated in industrial practice, which is why our study focuses on monomer recovery. In any case we have to face the challenge of ensuring that recycled fibres are cost competitive and/or that demand is created through recycled content mandates so that investments in sorting and recycling infrastructure can be adequately synchronised and are economically feasible over the long term (Nellström et al, 2022). As the combinations, complexity and absolute scale of the waste fibre flows increase, recycling will remain a challenge and cascade recycling options, for example pyrolytic downcycling of PET/elastane blends into industrial sorbents (Anceschi et al, 2025) may be environmentally preferable. As shown in this study, recycling operations, if not carefully engineered, can be climate intensive. Consequently, to improve the sustainability of the fashion industry, the focus needs to be broadened from the recycling of the waste to reforming the system at large. There are EU-directives that shape incentives for this, such as Design for Recycling (DfR), and Safe and Sustainable by Design (SSbD). Designing clothes with the intention of simplifying sustainable waste management would mean decreasing complexity of textile fibre blends and increasing the disclosure of its monomeric content. This would help optimise future recycling systems to decrease their climate impact. It is just as important to discuss the fast fashion business model, and the rate at which we consume clothes. Although the rate has accelerated dramatically since the 1990 s (Peters et al., 2021), companies such as Temu and Shein are attempting to accelerate that consumption rate even further, exacerbating the challenge to waste treatment systems and to our planetary boundaries (O'Neill et al, 2018). In the context of this study's results, it is probably more effective to aim to reduce these volumes before production rather than focus on the waste management end of the garment lifecycle.

3.4. Limitations

One limitation with this assessment is that the system boundary cuts off the assessment at recycled monomers. For effective communication with consumers it might be worthwhile to study the conversion back to textile fibres as well, to communicate the impact of the full lifecycle of a closed-loop recycling of these mixed synthetic textiles. To look at the full fibre-to-fibre lifecycle might be of interest both for textile industry and for process developers. However, this would also add assumptions and uncertainty to this prospective analysis.

Another limitation is the geographical setting in Sweden. This affects the results, for example through the use of the Swedish electricity mix. Another geographic setting of interest is EU at large, since many waste regulations are decided on this level. It would therefore be interesting to alter the modelling to target waste flows in EU and use technology, infrastructure and data in general from the EU. A different electricity mix, or a bigger waste flow for that matter which might be possible in an EU context, will alter the environmental assessment of the waste treatment system of the PET-elastane textiles. A further matter that might be important to put forward, is the general transition towards low carbon energy supplies. In a future setting with lower carbon emissions on account of electrification of background systems, an assessment of this sort could find lower climate impacts.

4. Conclusions

This analysis compared two approaches for recycling blended PET-elastane textile waste in what is to our knowledge the first LCA on recycling of elastane-rich sportswear into monomer chemical building blocks. The approach for recovering monomers from both fibres emitted 62% more greenhouse gas than its BAU alternative, while the PET-only approach emitted 98% more in a Swedish context. Under both approaches the differences are of the same scale as the sum of the uncertainties in the recycling and BAU analyses. Nevertheless, despite these uncertainties allowing that recycling might not be worse than BAU, they clearly show that recycling will not improve climate outcomes. This result is important given the industrial and regulatory focus on recycling as a means to achieving sustainability goals. We identified hotspots in the recycling systems (e.g. solvent production and hazardous waste management) to help prioritise future research and development efforts that may improve the sustainability of the systems under study, while also providing BAU benchmark performance thresholds against which other business models or engineering processes can be assessed in a prospective LCA context (Wickerts et al., 2021, provides a pedagogical example of the latter). Such assessments may contribute to learning about larger technical systems, to innovation and hopefully to systemic change in the fashion sector.

CRediT authorship contribution statement

Alina Ridderstad Nordberg: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Greg Peters:** . **Erik Klint:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation. **Efstathios Reppas-Chrysovitsinos:** Writing – review & editing, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Anna Edsberger:** Writing – review & editing, Supervision, Resources, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2026.115620.

Data availability

Data will be made available on request.

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