Engineering 58 (2026) 38–47

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Recycling of Polymeric Materials—Perspective

Recent Advances in the Chemical Recycling of Polyurethane Consumer Products

Anjana S. Sarala [a,b,*], Bjarke S. Donslund [a,*], Troels Skrydstrup [a,c,*]

[a] Department of Chemistry & Interdisciplinary Nanoscience Center (iNANO), Aarhus University, Aarhus 8000, Denmark
[b] School of Chemical Sciences, Mahatma Gandhi University, Kottayam 686560, India
[c] The Novo Nordisk Foundation CO_2 Research Center, Aarhus 8000, Denmark

ARTICLE INFO

Article history:
Received 8 April 2025
Revised 2 September 2025
Accepted 5 November 2025
Available online 27 December 2025

Keywords:
Recycling
Polyurethane
Circular economy
Depolymerization

ABSTRACT

Polyurethane (PU) is the most prevalent thermoset plastic material, accounting for approximately 6.3% of global plastic production. Recently, the closed-loop chemical recycling of PU has attracted considerable academic interest, as it offers a solution for plastic waste disposal and provides an alternative plastic-production pathway independent of fossil hydrocarbon sources. This perspective provides insight into our work on the chemical monomer recycling of PU plastic, with a focus on processes such as hydrogenation, acidolysis, and chem-solvolysis, primarily involving flexible PU foams as substrates. The challenges and opportunities of this field are discussed in the context of other relevant contributions, expressing our thoughts on the current scenario and the prospects of large-scale PU recycling in an industrial setting.

© 2025 THE AUTHORS. Published by Elsevier LTD on behalf of Chinese Academy of Engineering and Higher Education Press Limited Company. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Plastic products are ubiquitous today, thanks to their advantageous properties in logistics, food and water preservation, healthcare, and insulation. The global production of plastic in 2023 was 414 million tonnes, of which Europe contributed around 54 million tonnes [1]. With a plastic consumption rate of 107 kg per capita annually, the European Union (EU) is one of the largest consumers of plastics in the world [2]. The increasing production and consumption of plastics cause significant environmental harm and contribute to climate change. Thus, a circular economy is a key political priority for the EU in addressing the environmental, climate, and health impacts of increasing plastic production and consumption, as exemplified by the European plastics strategy [3]. The circularity of material in the economy can be calculated using the circular material use rate (CMUR), which denotes the proportion of total material use procured from recycled waste. The use of recycled plastic in the EU reached 14.8% in 2023, up from 8.1% in 2020 [3], due to a modest decrease in plastic consumption and a high uptake of recycled materials. Despite such improvements, most plastic production still relies on fossil-fuel feedstocks, accounting for 6% of global oil consumption and projected to reach 20% by 2050 [4]. A sustainable society requires a decrease in fossil-fuel dependency and a reduction in its carbon footprint. In this context, synthetic plastics attract considerable criticism—and rightfully so—due to the lack of sustainable recycling strategies and the resulting environmental impacts. Hence, it is high time we replace the nonrenewable resources used in plastic production with sustainable feedstocks and effectively implement the circular recycling of end-of-life (EoL) plastics to ensure a sustainable plastic ecosystem.

Knowledge of the various types of plastics is essential for understanding plastic recycling strategies. Based on their polymeric macro-structure, plastics are classified into thermoplastics and thermoset plastics. The linear chains in thermoplastics—such as polyethylene (PE), polypropylene (PP), polycarbonates (PC), and polyesters (e.g., polyethylene terephthalate (PET))—allow processing through dissolution or melting. Hence, the recycling and isolation of high-value non-virgin raw materials from thermoplastics are relatively well developed and industrial technology is being established, despite the challenges associated with sorting different types of materials and the presence of additives such as color and plasticizers [5–8]. In contrast, the cross-linked polymer networks in thermoset plastics—including polyurethanes (PUs), epoxy resins, vulcanized rubber, and melamine—make these plastics unmeltable once cured. This structural complexity renders the

* Corresponding authors.
E-mail addresses: anja@inano.au.dk (A.S. Sarala), donslund@chem.au.dk (B.S. Donslund), ts@chem.au.dk (T. Skrydstrup).

https://doi.org/10.1016/j.eng.2025.11.031
2095-8099/© 2025 THE AUTHORS. Published by Elsevier LTD on behalf of Chinese Academy of Engineering and Higher Education Press Limited Company.
This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

development of feasible circular recycling methods for thermoset plastics extremely difficult—a crucial issue in plastic recycling that must be addressed promptly and effectively to achieve the goal of circular plastic recycling.

PUs are the most widely used thermoset plastics due to their availability in various forms, including rigid, flexible, and molded foams, as well as elastomers, coatings, and adhesives [9,10]. The polymeric networks with interchain cross-linkages in PUs combine isocyanate and polyol monomers. Its ease of structural manipulation and flexibility in design enable PU to be applied in a wide range of products, from refrigerators and mattresses to sophisticated materials such as wind turbine blades and automotive components. The estimated global PU production in 2023 was 26 million tonnes, a significant portion of which is diverted to PU waste due to inadequate recycling methods [11]. Much of this PU waste is incinerated for energy recovery—a process that is inadvisable, as it produces toxic gases and causes the loss of carbon-based material. Another strategy is mechanical recycling, which involves grinding PU waste into powder or granules for use as fillers or substrates, and re-gluing shredded flexible foams under heat and pressure to create rebonded materials. While these methods effectively extend the lifespan of PU products, the resultant materials are of lower value than the original polymer [12,13]. Introducing advanced recycling methods is imperative to address these shortcomings [14].

In recent years, dynamic covalent bonds have been introduced to the cross-linked network of the PU frame to enable reprocessability by forming covalently adaptable networks (CANs) [15,16]. This has been achieved by incorporating new reversible linkages or by breaking and reforming carbamate bonds, which enable the network to be rearranged in response to an external stimulus such as heat. Dichtel et al. [17,18] were successful in transforming traditionally irreversible PU thermosets into CANs by using catalysts such as dibutyltin dilaurate (DBTDL) and *p*-toluenesulfonic acid (PTSA). These dynamically modified polymers can be reprocessed through techniques such as hot-pressing, reactive extrusion, or compression molding into new materials with minimal degradation in their mechanical properties [19,20]. Recent advances in the structure and properties of these materials are covered in the literature and lie beyond the scope of this perspective. Although these materials represent a promising future for parts of PU recycling, they still present challenges related to energy efficiency, scalability, compatibility with different types of PU, and the difficulties associated with processing mixed/contaminated PU materials. Therefore, the development of viable recycling strategies for conventional PU materials remains crucial to effectively address the persistent challenges associated with plastic waste management.

Recent reviews have addressed PU recycling with a focus on mechanical, chemical, and enzymatic degradation. Madbouly [21] highlighted the transformative potential of CANs, while Karrech and Zhou [22] identified a significant gap in the literature regarding sustainable EoL strategies for the PU used in offshore oil and gas infrastructure. Sardon et al. [23] critically evaluated the potential of chemical and biological PU depolymerization. In their review, Malucelli et al. [24] provided a comprehensive overview of many current and emerging strategies for recycling PUs. In this perspective, we specifically focus on the chemical depolymerization of commercial and EoL PU waste, with an emphasis on the chemical processes developed by our group and their potential for industrial implementation. In the coming sections, we describe our work in this field since 2020, situating it within the context of other relevant contributions. This is followed by an assessment of the associated environmental and economic considerations. We conclude with a discussion of the key challenges that persist and offer our perspective on future directions necessary to advance the chemical monomer recycling of PU materials.

One such advanced recycling method involves chemical intervention, in which the polymerization is reversed to generate monomers for the production of new PU materials, thereby partially closing the plastic production loop [25,26]. Chemical recycling processes include hydrolysis [27], aminolysis [28], and glycolysis [29], each providing a certain degree of PU waste recycling. During hydrolysis, PU reacts with water at high temperatures in the presence of a catalyst to yield a mixture of amine, polyol, and carbon dioxide (CO_2) [30]. The polyol is usually isolated as a mixture with aromatic compounds and thus requires further valorization to isolate both fractions separately. However, the isolated polyol is of sufficient quality to be adaptable as a substituent for virgin polyol. Nevertheless, its high energy input and the difficulties associated with water removal make this process uneconomical [24]. Recently, Evonik [31,32] employed a protocol involving a phase-transfer catalyst to achieve the alkaline hydrolysis of flexible PU foams under relatively mild conditions. In aminolysis, the PU waste is treated with ammonia or aliphatic amines to produce urea and polyol fractions. Unlike hydrolysis, this method separates the aromatic compounds from the polyol; however, it is limited to model substrates, and the presence of additives—even in small quantities—can disturb the recycling process [28]. Although a recent report on the microwave (MW)-assisted aminolysis of flexible PU foams showed promise in the quality of the recycled polyol, this method has several disadvantages, particularly regarding the toxicity of the reagents employed [33]. In glycolysis, PU material is treated with a diol and a catalyst at high temperatures, resulting in a polyol feed containing residual diols, polyols, carbamates, and anilines. The anilines are typically capped to prevent foaming and safety issues. This low-quality feed is used as a new polyol, following dilution with a sufficient amount of virgin polyol to satisfy the specific requirements for a new material [29,34]. Split-phase glycolysis allows for isolation of aniline free polyol by separating out small carbamates and most anilines through phase separation, thereby removing the aromatic fraction from the polyol. The resultant polyol is washed with aqueous acid and is of higher quality, allowing it to substitute for up to 50% of the virgin polyol in the subsequent production of materials [35–37].

Recent academic research—including ours—has proposed new methodologies and improvements for PU recycling. In the past five years, our group has focused on metal-catalyzed hydrogenation, acidolysis, and solvolysis to develop an enhanced method for PU recycling (Fig. 1). We were able to employ an earth-abundant transition-metal catalyst instead of a noble metal for PU hydrogenation [38]—a crucial milestone for achieving cost efficiency. The acidolysis/hydrolysis process yielded the recovery of 90% aniline and 98% polyol, resulting in the valorization of both the polyol and aniline fractions, unlike previous acidolysis processes where the amine adducts are typically incorporated within the polyol fraction, resulting in a low-quality recycled polyol [39]. The possibility of a closed-loop recycling process was established for the first time using a chem-solvolysis process, which produced a recycled polyol that could fully substitute for virgin polyol and maintain foam quality [40]. These results and those of other research groups are encouraging and point to the development of a mature thermoset recycling technology that facilitates the re-entry of materials into the product life cycle. Although exciting, it is worth noting that these laboratory-scale processes are still in the initial stages and require extensive life-cycle and techno-economic analyses before they can be scaled up for industrial use. Below, we describe our work in this field since 2020, situating it in the context of other relevant contributions; this is followed by a discussion of our perspective on the significant obstacles that remain.

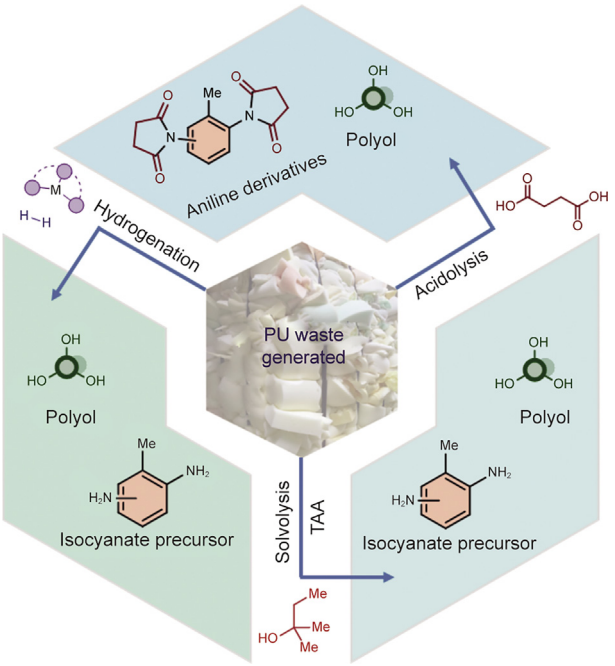

Fig. 1. Recent developments from our group in the chemical recycling of PU-based consumer products. TAA: *tert*-amyl alcohol; Me: methyl.

2. Transition-metal-catalyzed hydrogenation

Catalytic hydrogenation provides an atom-economical approach to PU recycling, as it avoids the production of stoichiometric waste associated with conventional reducing agents (Fig. 2) [41–45]. During this method, green hydrogen gas—produced from bio-based resources or water electrolysis—is used in conjunction with a metal catalyst to break the PU cross-linkages into polyols and amines under elevated temperature and pressure [46].

Milstein et al. [43] established a proof of concept for the hydrogenative depolymerization of PUs in 2020 using a ruthenium (Ru)–PNN catalyst (PNN = 2-(di-*tert*-butylphosphinomethyl)-6-(diethylaminomethyl)pyridine) under 70 bar (1 bar = 10^5 Pa) of hydrogen (H_2) at 150 °C for 2 days. The practical applications of this method are further limited due to the deactivation of dimethyl sulfoxide (DMSO) solvent on the Ru catalyst, which results in a lower turnover number (TON) and DMSO decomposition, leading to potential safety issues.

Following this seminal result, Schaub et al. [44] demonstrated the hydrogenation of a toluene diisocyanate (TDI)-based PU sponge using Ru–PNN catalysts at 100 bar of H_2 at 200 °C for 2 days in tetrahydrofuran (THF). A high reaction time ensured the polymer's solubility, resulting in almost complete conversion. Around the same time, our group [45] attempted the catalytic hydrogenation of various commercial and EoL PU samples, which are more complex due to extensive interchain cross-linkages, under 30 bar of H_2 at 150–180 °C for 21 h, using the commercially available iridium (Ir)–^{iPr}MACHO complex (^{iPr}MACHO = [HN($C_2H_4P^iPr_2$)$_2$]) as the catalyst. This method effectively hydrogenated all four types of PU samples (flexible solid, flexible foam, rigid solid, and rigid foam), isolating the polyol and aniline fractions. More importantly, the best results were obtained when isopropyl alcohol (^{i}PrOH)—a green solvent—was used.

Although these processes are promising and can proceed with the use of green hydrogen, their reliance on expensive and commercially impractical metal complexes and solvents, coupled with the low TON, hinders their prospects of large-scale implementation on an industrial setup. To reduce the cost, abundance, and toxicity issues associated with 4d and 5d metals, Schaub et al. [47]—concurrently with our group [38]—investigated the hydrogenation of PU samples utilizing two distinct catalysts involving the 3d metal manganese (Mn). While Schaub's team reported a Mn–PNN complex in THF at 200 °C for 24 h with potassium *tert*-butoxide (KO^{t}Bu) and 60 bar H_2, achieving TONs up to 78, we presented a maximum TON of 905 using an Mn–^{Ph}MACHO complex in ^{i}PrOH at 180 °C for 21 h with potassium hydroxide (KOH) and 50 bar H_2.

Despite the promising atom efficiency, transition-metal-catalyzed hydrogenation as a PU recycling strategy presents many challenges regarding industrial application. The high cost of metals and ligands, the difficulty in scaling up beyond the gram-scale, and the safety concerns associated with high-temperature and high-pressure reactions are significant obstacles. Developing a highly competent and cost-efficient catalyst with a good recycling capacity is necessary to meet these challenges. Without such a development, metal-catalyzed PU hydrogenation will likely remain limited to academic research rather than reaching industry as a feasible PU recycling solution. Efforts to mitigate some of these obstacles have been undertaken, such as by eliminating the need for pressurized hydrogen through the application of a transfer-hydrogenation system [48]. Very recently, a hydrogenative PU depolymerization employing a heterogeneous catalyst was described by Du et al. [49], which may facilitate catalyst recovery.

3. Chem-solvolysis

A circumstantial transcarbamoylation reaction, resulting in increased solubility of the polymeric fragments, was observed between ^{i}PrOH and the carbamate groups of PU during our work on the Mn-catalyzed hydrogenation of PU. This mechanism explains the high TON we observed, compared with the Schaub group's report using THF or THF/toluene mixtures [38,47]. The similarity of the adducts formed during this reaction to *tert*-butyloxycarbonyl (Boc) amine-protecting groups prompted us to attempt their removal under high-temperature conditions. After a thorough optimization of various alcohol-based solvents and other reaction conditions, we found that reacting flexible PU foam in *tert*-amyl alcohol (TAA) at 225 °C for 2.25 h in the presence of a catalytic amount of KOH resulted in complete depolymerization, affording a yield of over 95% toluenediamine (TDA) (Fig. 3). The applicability of this process was demonstrated by depolymerizing 20 different PU materials, encompassing both rigid and flexible foams and solids, with the flexible foam successfully processed on a 50 g scale without compromising the polyol quality. As TAA can be easily removed from the system, this new PU-recycling process can be considered an improvement over the industrially established alcohol-based glycolysis [50].

In a follow-up study, we presented our efforts to achieve a recycled polyol through the TAA solvolysis of PU foams and its application in scaling to produce new thermoset PU foams. Without altering the recipe, a complete substitution of virgin polyol with recycled polyol could be enabled to synthesize new foam with comparable mechanical and physical properties. The new foam prepared from the recycled polyol was further depolymerized to recover the polyol, demonstrating the feasibility of forming a closed-loop polyol-recycling process [40]. This report establishes the isolation of virgin grade polyols and spectroscopically pure amines from the depolymerization of foams from second-generation materials. Although the reuse of polyols has been established, the same has not yet been achieved for amines, which could be used as precursors for generating new isocyanates. To

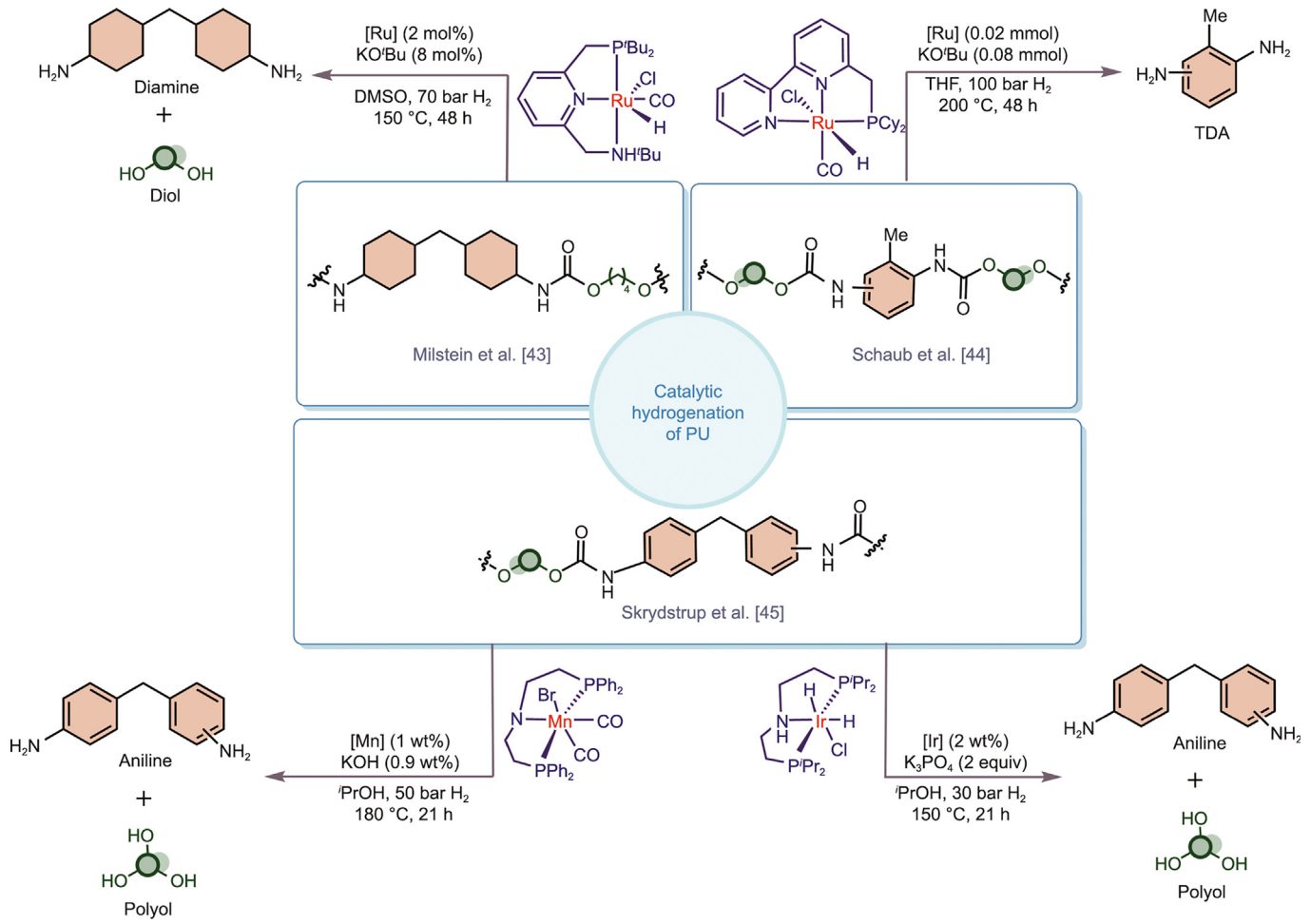

Fig. 2. Catalytic hydrogenation processes of flexible PU foams. Bu: butyl; Cy: cyclohexyl; DMSO: dimethyl sulfoxide; equiv: equivalent; Ph: phenyl; Pr: propyl; THF: tetrahydrofuran; TDA: toluenediamine.

summarize, TAA solvolysis directly provides polyols and diamines without the need for expensive catalysts, purification methods, or excess water, thereby establishing a new recycling method with the potential to achieve a circular economy for PU.

Most EoL products in the textile industry end up in landfills or are incinerated, with fiber-to-fiber recycling generally accounting for less than 1% [51,52]. Although recycling possibilities are available for single-component fibers, the inclusion of mixed fibers—especially those containing the stretchable synthetic fiber elastane—hinders efficient recycling [53–55]. Though often used in small quantities (< 3%) and always in combination with other textile materials, elastane is present in 20% of waste clothing articles, and this proportion is expected to increase to 30% by 2030 [51,56]. Elastane is a PU–urea block copolymer synthesized from 4,4′-methylenediisocyanate (MDI) and a macrodiol. It comprises approximately 80%–85% flexible diol (soft segment), and the remaining urea groups (hard segment) form a polymer network through hydrogen bonding, resulting in a molecular structure similar to that of flexible PU solids [57]. Hence, circular economy efforts for PU could motivate the development of possible recycling methods for elastane, which currently has only a few chemical recycling options. The selective depolymerization of PET–elastane blended textiles using CH_2Cl_2/EtOH or THF/ethylene glycol solvent systems with KOH was recently reported, affording ethylene glycol and terephthalic acid components [58,59]. This method leaves elastane fibers, allowing them to possibly be melted and extruded into new fibers. Wang et al. [60] later demonstrated elastane decomposition in PET glycolysis and its depolymerization into 4,4′-methylenedianiline (4,4′-MDA), polytetrahydrofuran, and 2-imidazolidone. Solvolysis using problematic amide solvents such as *N*,*N*-dimethylformamide (DMF) can also remove elastane from nylon or cotton. However, the energy expense of removing high-boiling solvents and the compromised quality of the remaining fibers make this a less-desirable recycling option [61,62].

We extended our chem-solvolytic studies on PU depolymerization using TAA to disassemble elastane, first from virgin elastane and then from mixed textiles [63]. The success of the method depended on the recovery of major fabric components such as polyester or cotton, together with the isolation of elastane monomers for repolymerization. Since the solvolysis medium primarily consists of a weak nucleophile, we hypothesized that the functional groups of the major textile component might be preserved even at elevated temperatures. This method proved successful for polyamide textiles, and preliminary results indicated potential for cellulosic textiles as well. However, further optimization is necessary to determine the ease and applicability of this methodology and—crucially—the quality of the isolated materials.

In this method, solvolysis can remove and depolymerize elastane from textiles, allowing for possible repolymerization and reuse in new elastane fibers. TAA solvolysis and other innovative methods could reduce the dependence on fossil fuels for fabric manufacture by enabling the re-entry of waste fractions into the production cycle. Nonetheless, further studies are essential to reduce the energy demand of the process and preserve the remaining textiles, excluding nylon.

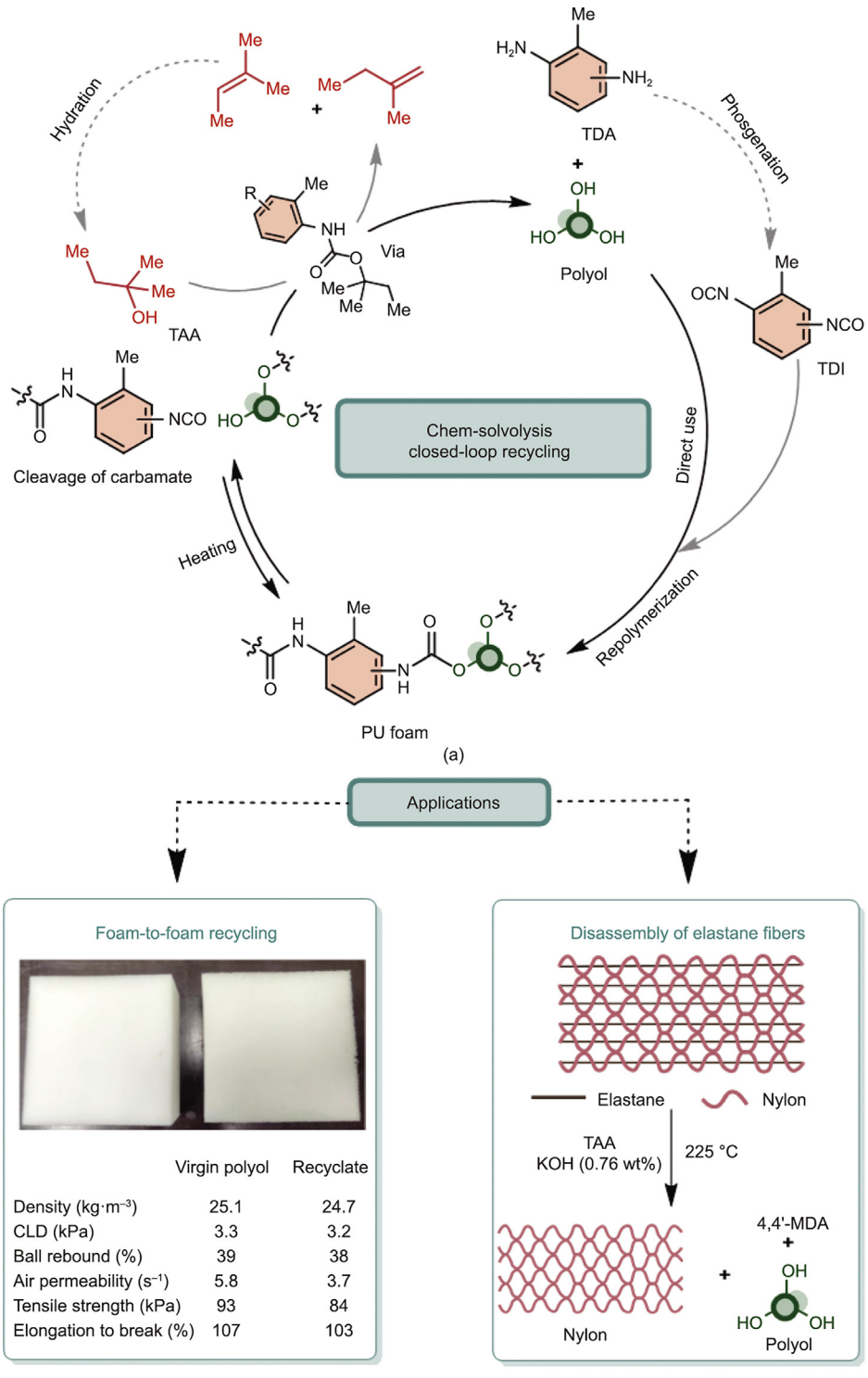

Fig. 3. (a) Closed-loop recycling of PU foam using TAA solvolysis and (b) its applications. CLD: cross-link density; 4,4′-MDA: 4,4′-methylenedianiline.

4. Acidolysis

PU waste may be valorized by reacting with organic diacids to produce polyol, acid-tethered solids, and CO_2. This method is known as acidolysis and has been widely used in academia and industry for recycling PU foams (Fig. 4) [64,65]. These reactions are typically carried out in neat acids at a range of temperatures, depending on the choice of acid. Although mineral acids like hydrochloric acid (HCl) can operate at lower temperatures (~60 °C), organic dicarboxylic acids (DCAs) usually require temperatures of 190–210 °C. The choice of acid usually determines the nature of additional products as well [66]. Acidolysis is a relatively mature recycling process and has been operated at pilot scale by Dendro Poland and H&S Anlagentechnik [67]. A second-generation version involving a mixed acidolysis/glycolysis approach is also being scaled industrially by several companies.

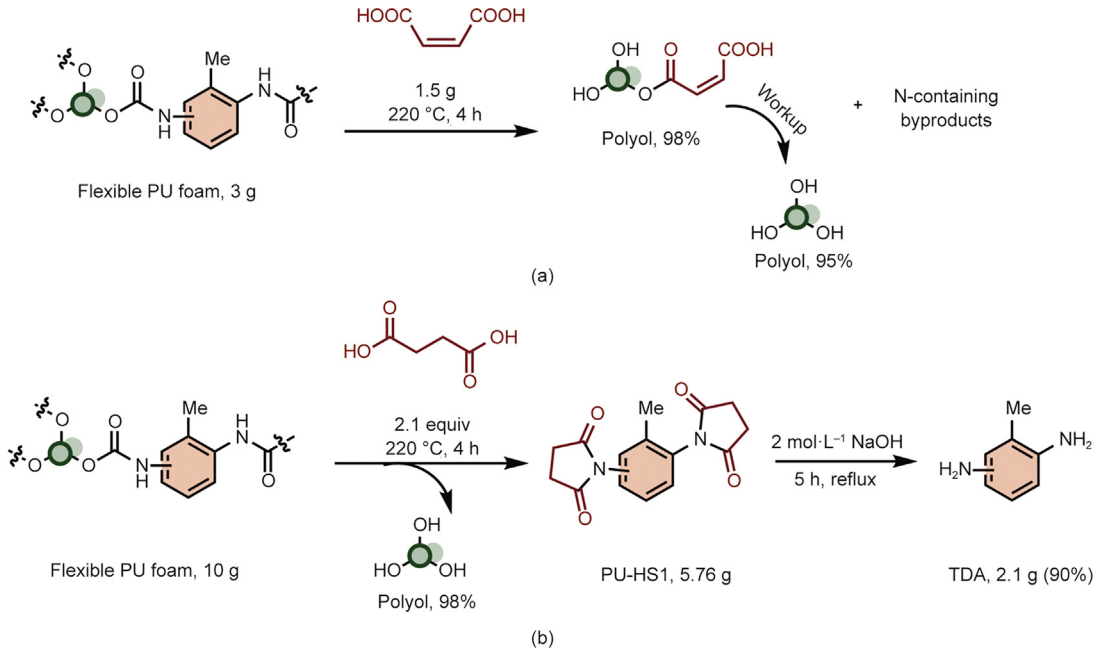

Fig. 4. Acidolysis of PU foam with (a) maleic acid, forming polyol esters and amide coproducts, and (b) succinic acid, forming succinimide and polyol.

Abu-Omar et al. [68] recently presented a noteworthy improvement in flexible foam recycling by delivering an efficient acidolysis reaction using neat maleic acid (MA), which finishes in less than 15 min at 175 °C under 1 atm (1 atm = 101 325 Pa) of nitrogen (N_2). This method fully degrades the foam into recycled polyol esters and amides, achieving a mass balance of 98%, including the stoichiometric evolution of CO_2. Hydrolysis of the ester, followed by separation, yielded virgin-grade polyol; valorization of the amide coproduct resulted in TDA. Hence, this process could be considered a closed-loop recycling of foams using acidolysis.

The overall efficiency of acidolysis is affected by the esterification of the formed polyol, which increases the number of steps in the recycling process. Abu-Omar et al. [69] utilized DCA vapor at temperatures below its melting point (< 150 °C) to address this issue. The polyol obtained was not esterified, making it suitable for reuse without further treatment.

Our work on acidolysis focused on the isolation and valorization of the dianiline component constituting the hard segment of PU—an area that is generally neglected in literature. Treatment of flexible PU foam with succinic acid at 220 °C for 4 h yielded polyol and a solid succinimide-tethered diamine intermediate [39]. Succinimide formation was not previously described in the literature on acidolysis. Since this eliminates the possibility of a second reaction from the DCA, it has a significant impact on the reaction stoichiometry and the ease with which polyol quality can be controlled through knowledge of said stoichiometry. For conversion of the solid succinimide, metal-catalyzed hydrogenation or hydrolysis was used to access TDA, resulting in an 83 wt% recovery of polyol and dianiline. Based on matrix-assisted laser desorption/ionization (MALDI) and infrared (IR) spectral analyses of the recovered polyols, the succinic acid was determined to provide significantly higher quality polyols than the other DCAs tested, and it was hypothesized that it is directly linked to the formation of succinimides. Encouraging results were observed for rigid PU foam and rebonded flexible foam acquired from a commercial source.

An ensuing report by Abu-Omar et al. [70] investigated the fate of the nitrogen-containing aromatics during the acidolysis of PU foams with DCAs and shed light on their formation kinetics and structural distribution. Their studies employing glutaric acid (C_5-DCA) and succinic acid (C_4-DCA) concluded that diimide formation occurs in both cases, while adipic acid (C_6-DCA) does not lead to imide formation. For succinic acid, only diimide is observed, whereas an amide–imide intermediate is identified for glutaric acid, demonstrating high sensitivity to the distance between the two carboxylic acids. These results corroborate our observations regarding the formation of a desirable imide intermediate, which could be easily filtered from the polyol fraction and hydrolyzed to obtain amines.

These new insights are encouraging and may pave the way for the modeling and scaling of flexible PU foam chemical recycling via acidolysis to establish a circular plastics economy. However, the diacid's sacrificial reagent status and the workup procedure required to re-enter anilines and solvents into the recycling protocol may limit the process's operability.

5. Comparison of methodologies

Table 1 presents a simplified overview of the depolymerization processes discussed above, including benefits and drawbacks. Glycolysis is included as the established reference. Notably, variants have been developed for most of these processes, which deviate from some of the points in the table.

Transitioning to advanced chemical recycling with the potential for recovering both monomers centers on the challenge of separation and purification. Methods offering purification advantages are likely to be the most useful. For depolymerization methods such as hydrogenation, chem-solvolysis, and hydrolysis that provide free anilines, a very high purity is a prerequisite to proceed to phosgenation. Hence, robust purification protocols and rigorous quality control must be ensured, especially for EoL materials, which may contain unknown impurities. Scaling methods such as acidolysis (or aminolysis), which produce solid nitrogen-containing fractions, present the engineering challenge of adapting and developing filtration or centrifugation technologies to enable efficient polyol recovery without the excessive use of organic solvents. Particularly for mixed-material input, differences in polyol viscosity and polarity may prove challenging in this context. Currently, our group works in close collaboration with industry and municipality

Table 1
Comparison of conditions and reaction outcomes for the classic glycolysis, hydrogenation, acidolysis, and chem-solvolysis of PU.

Method	Catalysts and reagents	Reaction conditions	Main products	Benefits	Drawbacks
Glycolysis	Glycol, KOH, metallic Lewis acids or amine-based catalysts	180–220 °C, atmospheric pressure	• New polyols incorporating N-containing aromatics	• No purification other than amine-capping • Well-established	• Polyol output significantly different from virgin material • Isocyanate precursors not recovered
Hydrogenation	Ru-, Ir-, and Mn-pincer complexes	130–200 °C, 30–100 bar H_2, polar solvents	• Polyols • Anilines • Methanol	• Excellent atom economy with no CO_2 formation • Direct recovery of both monomers	• Expensive catalysts, equipment, and purification • High pressure
Acidolysis	Organic diacids (e.g., succinic or adipic acid)	150–220 °C, atmospheric pressure	• Polyols • Cyclic imides or amide-tethered anilines • CO_2	• Simple purification by centrifugation or filtration • Solvent free	• Difficult recovery of anilines and diacids • Risk of polyol esterification
Chem-solvolysis with TAA	TAA (solvent/reactant), KOH	225 °C, potential pressure build-up to 20–30 bar depending on specific setup	• Polyols • Anilines • Amylenes • CO_2	• Broad PU compatibility • Direct recovery of both monomers • 100% substitution in polyol demonstrated	• Extensive product purification • Recovery/reforming of TAA • Pressure build-up

partners in the PURfection consortium, as we attempt to address some of the issues discussed above and work with actual mixed municipality PU waste.

6. Life-cycle and economic considerations

Although chemical degradation processes for PU present a potentially more sustainable alternative to incineration and landfilling, their implementation is often hindered by substantial capital investment requirements, which elevate the cost of recycled products and limit their practical significance. To evaluate the feasibility and sustainability of these processes, life-cycle assessments (LCAs) and techno-economic analyses (TEAs) serve as critical methodological tools. LCAs enable the quantification of environmental impacts, including toxicity, greenhouse gas emissions, and resource depletion, while TEAs provide insights into scalability, industrial competitiveness, and economic viability. Balancing the trade-offs identified through these assessments is crucial for developing a truly sustainable recycling strategy and plays a pivotal role in informed decision-making [71]. Though highly useful, these analyses present challenges including data gaps, inconsistent methodologies, and limited comparability across studies. To address these issues, a recent report proposed integrated frameworks, detailed checklists, and methodological recommendations aimed at improving transparency, comprehensiveness, and consistency [72,73]. A 2024 study by Bardow et al. [74] on the environmental potential of the chemical recycling of PU rigid foam indicated that the recovery of polyol and isocyanate monomers could potentially reduce climate change impacts by 3.8–5.6 kg CO_2 equivalent per kilogram PU treated, clearly outperforming traditional methods such as incineration and landfill. However, recycling PU into early precursors, such as benzene and aniline, may result in the burden shifting, with half of the analyzed environmental parameters—including toxicity and resource depletion—increasing. Hence, their study underlined the importance of product prioritization and selective depolymerization, emphasizing that recycling—which yields high-value reusable monomers—provides the most significant environmental benefits.

Glycolysis is a widely adopted PU-recycling method due to its low energy requirements and mild reaction conditions, which contribute to a moderate climate impact from an LCA perspective. However, its environmental benefits are limited by the downcycling of polyols and the presence of contaminants and catalysts, which reduce product quality and circularity [75]. From a TEA standpoint, glycolysis is economically favorable, with low capital and operational costs that support decentralized implementation. Nonetheless, its economic efficiency is offset by its inability to recover isocyanate precursors and the non-virgin-type polyols it forms, generally restricting its applicability to lower-value products and diminishing its market competitiveness [76,77].

The depolymerization methods described in the previous sections have not yet been subjected to thorough TEA and LCA studies, and the following are qualitative assessments based on our learnings. Unlike the example of glycolysis, these methods have not been scaled; in particular, the exact purification methods used will have huge impacts in these three cases. The metal-catalyzed hydrogenation of PU offers high-purity polyol recovery and excellent material circularity, making it one of the most effective strategies from a product-quality standpoint. However, its high energy requirements and reliance on high-pressure conditions contribute significantly to the environmental burden. The use of expensive metals (Ir, Ru) further complicates its sustainability profile. While hydrogenation delivers superior monomer recovery, its economic viability is challenged by high operational costs and the need for specialized infrastructure. Emerging research into more affordable transition metals, such as manganese, holds promise for reducing costs and improving scalability; however, industrial adoption appears unlikely due to the complexity of purification and the capital-intensive nature of the process. Compared with these two processes, acidolysis holds greater potential for environmental sustainability, especially when it can valorize both polyol and diamine fractions under moderate conditions. Acidolysis offers a balanced cost profile, as the process benefits from relatively simple purification methods such as centrifugation and filtration, although the recovery of anilines and diacids remains energy-intensive and challenging thus far. The acidolysis–hydrolysis variant improves monomer recovery and may simplify purification. Although this modification introduces wastewater production and increased energy input, it may still result in improved environmental performance due to the absence of complex byproducts. Its scalability remains dependent on efficient downstream processing and valorization strategies. Chem-solvolysis requires moderate energy input and delivers high recovery. Its compatibility with various PU waste streams and its closed-loop potential contribute to

reduced material toxicity, resource depletion, and CO_2 emissions. This process may be economically attractive, as it avoids the use of expensive catalysts and relies on simple reagents with high solvent efficiency. However, its purification strategy—particularly the recovery and reuse of TAA—is energy-intensive and may affect overall process economics.

Overall, each PU recycling method presents distinct advantages and limitations based on environmental and economic considerations. Acidolysis could offer promising life-cycle profiles, combining moderate energy input and high recovery rates with relatively low environmental impacts. From a TEA perspective, glycolysis remains the most accessible approach due to its low capital and operational costs, although its limited circularity and lack of purification reduce its competitiveness. Acidolysis and TAA-based solvolysis might strike a more favorable balance between cost, performance, and sustainability. At the same time, hydrogenation—despite delivering both monomers and excellent circularity—is constrained by high energy demands and expensive infrastructure. Selecting an optimal recycling strategy requires balancing material recovery and product quality with ecological footprint and resource efficiency. Hybrid approaches and process optimization may be necessary to align LCA and TEA goals.

7. Industrially viable closed-loop recycling of PU-based consumer products: Challenges and opportunities

Industrial methods for chemical PU recycling have primarily focused on producing a new polyol that incorporates aromatics originating from isocyanates (Fig. 5, top). These methods include glycolysis followed by capping free amines with epoxides, and glycoacidolysis where the amines are capped *in situ*. The advantage of these methods is that they circumvent complex purification steps and avoid waste formation. However, low polyol quality—which has generally been addressed by dilution with virgin polyol—and the inherent inability to provide circularity in isocyanates limit the applicability of these methods. Recent initiatives to recycle post-consumer products through these means are essential for creating infrastructure and knowledge regarding the sorting and sourcing of feedstock and for establishing value chains. Learnings regarding impurities at both the macroscopic (e.g., latex mattresses) and molecular levels (fillers, fire retardants, toxic legacy catalysts, etc.) will likely be translated directly to the next generations of chemical recycling methods.

With several advances made in the past few years in the chemical recycling of PU (Fig. 5, bottom), it is tempting to state that the problem is close to being solved and it should be possible to move to circular solutions. However, this may be a stretch. Significant challenges remain before the solutions—often developed in academia–industry collaborations—can flourish at scale. Among others, these challenges include sorting and logistics related to feedstock handling, energy demand, the presence of legacy additives and catalysts, cost-effective separation of polyol and aromatic fractions, the application of mixed polyols from EoL products, and the recycling of anilines to isocyanates. In this discussion, we will touch on the latter three subjects.

The cost-effective separation of aromatics and polyols is a significant hurdle on the path to the next generation of chemical PU recycling. On a laboratory scale, we and others have demonstrated that it is possible to separate the two; however, applying multiple liquid–liquid extractions and similar techniques within a reasonable economic frame on a larger scale is challenging. It is also essential to differentiate between recycling industrial waste (e.g., cut-offs) and EoL waste, as further complications are expected for the latter.

As mentioned, anilines have been isolated following the deconstruction of PU. However, no demonstration of their application in phosgenation and subsequent reformulation has been reported thus far, to the best of our knowledge. For us and presumably for others, this is linked to the dangers associated with phosgenation at a sufficient scale to deliver enough material for reformulation. We believe industry collaboration will be key in enabling this important step. While some polyols may be obtained from renewable sources or incorporate CO_2, aromatics are more challenging to source sustainably and will, in the long run, be crucial to recycle rather than incorporating them into new polyols. For flexible foam, aromatics are a minor component, but for rigid foam, they are a significant constituent; in this case, it would be unsatisfactory not to obtain and valorize this key fraction. Handling and transporting toxic anilines is costly, and the formation of free anilines during

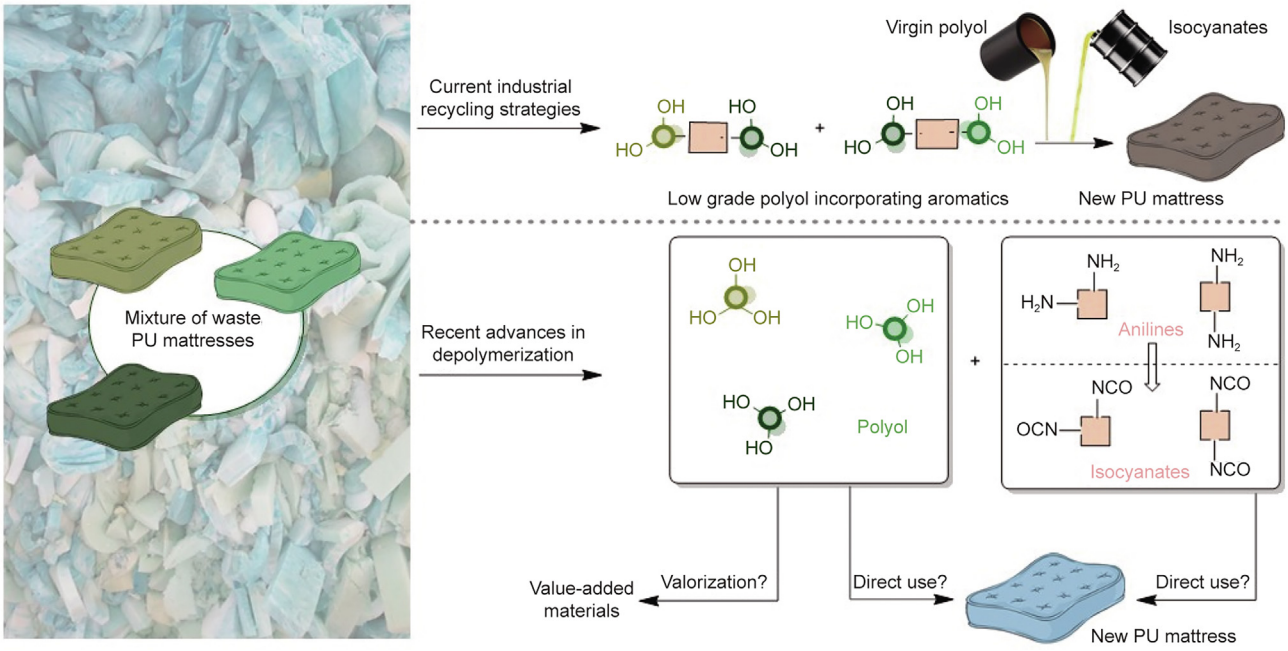

Fig. 5. Current recycling strategies for PU foams and proposed possibilities for waste fractions to enter value streams, resulting in effective closed-loop recycling.

depolymerization may hinder aniline application at smaller sites. Hence, to achieve aromatic circularity, it may be beneficial to apply protocols such as acidolysis or aminolysis to locally retrieve the polyol fraction, while solid amide-bound aromatics may be transported to larger hubs for further processing to finally yield recycled isocyanates.

While a handful of different isocyanates are used in PU foam production, a wide array of polyols are employed, raising the issue of the fate of mixed polyols (Fig. 5, bottom). Separating different polyols appears to be an unlikely solution, but separating mixed polyols from aromatics should be possible, albeit difficult. The quality and uses of the ensuing polyol mix arising from EoL mattresses will be interesting to investigate. The outcome is likely to vary over time and with location due to differences in feedstock; moreover, depending on purification techniques, additives may persist. To the best of our knowledge, investigations of this sort have not been reported. Is a mixed polyol best suited for reformulating new mattresses, and will it be possible to develop recipes for reformulations that do not require excessive dilution with virgin polyol? Or will it be necessary to valorize this new polyol fraction in other ways? These are some of the interesting questions that must be addressed in the long run; by doing so, we believe it is possible to find a sustainable solution to chemical PU recycling.

8. Outlook

The methods industrially applied for the chemical recycling of PU are inherently non-circular. Recent academic approaches to the closed-loop recycling of PU may provide a sustainable alternative, provided they yield favorable LCA and TEA results. A methodology that provides a cost-effective and sustainable separation of polyols and aromatics, allowing both fractions to be reused or valorized, is crucial for achieving circularity in PU recycling.

CRediT authorship contribution statement

Anjana S. Sarala: Writing – review & editing, Writing – original draft, Conceptualization. **Bjarke S. Donslund:** Writing – review & editing, Writing – original draft, Conceptualization. **Troels Skrydstrup:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Troels Skrydstrup's reports were provided by Aarhus University. Troels Skrydstrup is an Editorial Board Member for this journal and was not involved in the editorial review or the decision to publish this article. The other 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.

Acknowledgments

We are grateful for financial support by Villum Fonden (VIL71056), Innovation Fund Denmark to the PURfection consortium, the Novo Nordisk Foundation (NNF21SA0072700), and Aarhus University.

References

[1] Plastics—the fast facts 2024 [Internet]. Brussels: Plastics Europe; 2024 [cited 2025 Mar 24]. Available from: https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2024/.
[2] Plastics [Internet]. Paris: Organisation for Economic Co-operation and Development; [cited 2025 Mar 14]. Available from: https://www.oecd.org/en/topics/plastics.html.
[3] The role of plastics in Europe's circular economy [Internet]. Copenhagen: European Environment Agency; 2024 Jun 18 [cited 2025 Mar 20]. Available from: https://www.eea.europa.eu/publications/the-role-of-plastics-in-europe.
[4] Ellen MacArthur Foundation. The new plastics economy: rethinking the future of plastics. Cowes: Ellen MacArthur Foundation; 2016.
[5] Jagadeesh P, Mavinkere Rangappa S, Siengchin S, Puttegowda M, Thiagamani SMK, Rajeshkumar G, et al. Sustainable recycling technologies for thermoplastic polymers and their composites: a review of the state of the art. Polym Compos 2022;43(9):5831–62.
[6] Ellis LD, Rorrer NA, Sullivan KP, Otto M, McGeehan JE, Román-Leshkov Y, et al. Chemical and biological catalysis for plastics recycling and upcycling. Nat Catal 2021;4(7):539–56.
[7] Ragaert K, Delva L, Van Geem K. Mechanical and chemical recycling of solid plastic waste. Waste Manag 2017;69:24–58.
[8] Zhao YB, Lv XD, Ni HG. Solvent-based separation and recycling of waste plastics: a review. Chemosphere 2018;209:707–20.
[9] Gama NV, Ferreira A, Barros-Timmons A. Polyurethane foams: past, present, and future. Materials 2018;11(10):1841.
[10] de Souza FM, Sulaiman MR, Gupta RK. Materials and chemistry of polyurethanes. In: Gupta RK, editor. Materials and chemistry of flame-retardant polyurethanes. Volume 1: a fundamental approach. Washington, DC: ACS Publications; 2021. p. 1–36.
[11] Polyurethane demand worldwide from 2012 to 2024 [Internet]. New York City: Satatista Inc.; 2020 May [cited 2025 Jan 20]. Available from: https://www.statista.com/statistics/747004/polyurethane-demand-worldwide/.
[12] Morici E, Dintcheva NT. Recycling of thermoset materials and thermoset-based composites: challenge and opportunity. Polymers 2022;14(19):4153.
[13] Oliveux G, Dandy LO, Leeke GA. Current status of recycling of fibre reinforced polymers: review of technologies, reuse and resulting properties. Prog Mater Sci 2015;72:61–99.
[14] Wang B, Wang Y, Du S, Zhu J, Ma S. Upcycling of thermosetting polymers into high-value materials. Mater Horiz 2023;10(1):41–51.
[15] Durand-Silva A, Smaldone RA. Recycling the unrecyclable with dynamic covalent chemistry. ACS Cent Sci 2020;6(6):836–8.
[16] Miravalle E, Bracco P, Brunella V, Barolo C, Zanetti M. Improving sustainability through covalent adaptable networks in the recycling of polyurethane plastics. Polymers 2023;15(18):3780.
[17] Kim S, Li K, Alsbaiee A, Brutman JP, Dichtel WR. Circular reprocessing of thermoset polyurethane foams. Adv Mater 2023;35(41):2305387.
[18] Sheppard DT, Jin K, Hamachi LS, Dean W, Fortman DJ, Ellison CJ, et al. Reprocessing postconsumer polyurethane foam using carbamate exchange catalysis and twin-screw extrusion. ACS Cent Sci 2020;6(6):921–7.
[19] Zheng N, Fang Z, Zou W, Zhao Q, Xie T. Thermoset shape-memory polyurethane with intrinsic plasticity enabled by transcarbamoylation. Angew Chem Int Ed 2016;55(38):11421–5.
[20] Nettles JA, Alfarhan S, Pascoe CA, Westover C, Madsen MD, Sintas JI, et al. Functional upcycling of polyurethane thermosets into value-added thermoplastics via small-molecule carbamate-assisted decross-linking extrusion. JACS Au 2024;4(8):3058–69.
[21] Madbouly SA. Novel recycling processes for thermoset polyurethane foams. Curr Opin Green Sustain Chem 2023;42:100835.
[22] Karrech A, Zhou H. A systematic review on the recycling of polyurethane products from offshore applications. Circ Econ 2025;4(1):100129.
[23] Polo Fonseca L, Duval A, Luna E, Ximenis M, De Meester S, Avérous L, et al. Reducing the carbon footprint of polyurethanes by chemical and biological depolymerization: fact or fiction? Curr Opin Green Sustain Chem 2023;41:100802.
[24] Rossignolo G, Malucelli G, Lorenzetti A. Recycling of polyurethanes: where we are and where we are going. Green Chem 2024;26(3):1132–52.
[25] Gadhave RV, Srivastava S, Mahanwar PA, Gadekar PT. Recycling and disposal methods for polyurethane wastes: a review. Open J Polym Chem 2019;9(2):39–51.
[26] Datta J, Kopczyńska P. From polymer waste to potential main industrial products: actual state of recycling and recovering. Crit Rev Environ Sci Technol 2016;46(10):905–46.
[27] Yang LS, Macarevich DA, inventors; Lyondell Chemical Technology LP, assignee. Hydrolysis of polyurethanes. United States patent US 5208379A. 1993 May 4.
[28] Olazabal I, González A, Vallejos S, Rivilla I, Jehanno C, Sardon H. Upgrading polyurethanes into functional ureas through the asymmetric chemical deconstruction of carbamates. ACS Sustain Chem Eng 2023;11(1):332–42.
[29] Donadini R, Boaretti C, Scopel L, Lorenzetti A, Modesti M. Deamination of polyols from the glycolysis of polyurethane. Chem Eur J 2024;30(3):e202301919.
[30] Campbell GA, Meluch WC. Polyurethane foam recycling. Superheated steam hydrolysis. Environ Sci Technol 1976;10(2):182–5.
[31] Hildebrand J, Terheiden A, Hinrichs-Tontrup N, Pfefferle W, inventors; Evonik Operations GmbH, assignee. New depolymerization method for polyurethane. International patent WO 2022/042910A1. 2022 Mar 3.
[32] Hildebrand J, Terheiden A, Hinricks-Tontrup N, Pfefferle W, inventors; Evonik Operations GmbH, assignee. Depolymerization of polyurethane under mild conditions. International patent WO 2022/042909 A1. 2022 Mar 3.
[33] Grdadolnik M, Zdovc B, Drinčić A, Onder OC, Utroša P, Ramos SG, et al. Chemical recycling of flexible polyurethane foams by aminolysis to recover high-quality polyols. ACS Sustain Chem Eng 2023;11(29):10864–73.

[34] Heiran R, Ghaderian A, Reghunadhan A, Sedaghati F, Thomas S, Haghighi A. Glycolysis: an efficient route for recycling of end of life polyurethane foams. J Polym Res 2021;28(1):22.
[35] Molero C, de Lucas A, Rodríguez JF. Recovery of polyols from flexible polyurethane foam by "split-phase" glycolysis with new catalysts. Polym Degrad Stabil 2006;91(4):894–901.
[36] Vanbergen T, Verlent I, De Geeter J, Haelterman B, Claes L, De Vos D. Recycling of flexible polyurethane foam by split-phase alcoholysis: identification of additives and alcoholyzing agents to reach higher efficiencies. ChemSusChem 2020;13(15):3835–43.
[37] Molero C, de Lucas A, Rodríguez JF. Recovery of polyols from flexible polyurethane foam by "split-phase" glycolysis: study on the influence of reaction parameters. Polym Degrad Stabil 2008;93(2):353–61.
[38] Gausas L, Donslund BS, Kristensen SK, Skrydstrup T. Evaluation of manganese catalysts for the hydrogenative deconstruction of commercial and end-of-life polyurethane samples. ChemSusChem 2022;15(1):e202101705.
[39] Bech TB, Donslund BS, Kristensen SK, Skrydstrup T. Chemical separation of polyurethane via acidolysis—combining acidolysis with hydrolysis for valorisation of aromatic amines. Green Chem 2024;26(14):8395–404.
[40] Johansen MB, Donslund BS, Larsen E, Olsen MB, Pedersen JAL, Boye M, et al. Closed-loop recycling of polyols from thermoset polyurethanes by *tert*-amyl alcohol-mediated depolymerization of flexible foams. ACS Sustain Chem Eng 2023;11(29):10737–45.
[41] Kosloski-Oh SC, Wood ZA, Manjarrez Y, de los Rios JP, Fieser ME. Catalytic methods for chemical recycling or upcycling of commercial polymers. Mater Horiz 2021;8(4):1084–129.
[42] Cabrero-Antonino JR, Adam R, Papa V, Beller M. Homogeneous and heterogeneous catalytic reduction of amides and related compounds using molecular hydrogen. Nat Commun 2020;11:3893.
[43] Kumar A, von Wolff N, Rauch M, Zou YQ, Shmul G, Ben-David Y, et al. Hydrogenative depolymerization of nylons. J Am Chem Soc 2020;142:14267–75.
[44] Zhou W, Neumann P, Al Batal M, Rominger F, Hashmi ASK, Schaub T. Depolymerization of technical-grade polyamide 66 and polyurethane materials through hydrogenation. ChemSusChem 2021;14(19):4176–80.
[45] Gausas L, Kristensen SK, Sun H, Ahrens A, Donslund BS, Lindhardt AT, et al. Catalytic hydrogenation of polyurethanes to base chemicals: from model systems to commercial and end-of-life polyurethane materials. JACS Au 2021;1(4):517–24.
[46] Zainzinger V. Making green hydrogen work. Chem Eng News 2020;98 (23):20–2.
[47] Zubar V, Haedler AT, Schütte M, Hashmi ASK, Schaub T. Hydrogenative depolymerization of polyurethanes catalyzed by a manganese pincer complex. ChemSusChem 2022;15(1):e202101606.
[48] Liu X, Werner T. Indirect reduction of CO_2 and recycling of polymers by manganese-catalyzed transfer hydrogenation of amides, carbamates, urea derivatives, and polyurethanes. Chem Sci 2021;12(31):10590–7.
[49] An W, Liu X, Zhang X, Gao R, Chen Z, Hou Y, et al. Catalytic deconstruction of commercial and end-of-life polyurethane with heterogeneous hydrogenation catalyst. ChemSusChem 2025;18(9):e202402321.
[50] Johansen MB, Donslund BS, Kristensen SK, Lindhardt AT, Skrydstrup T. *tert*-Amyl alcohol-mediated deconstruction of polyurethane for polyol and aniline recovery. ACS Sustain Chem Eng 2022;10(34):11191–202.
[51] Ellen MacArthur Foundation. A new textiles economy: redesigning fashion's future. Report. Cowes: Ellen MacArthur Foundation; 2017.
[52] Lange JP. Managing plastic waste—sorting, recycling, disposal, and product redesign. ACS Sustain Chem Eng 2021;9(47):15722–38.
[53] Harmsen P, Scheffer M, Bos H. Textiles for circular fashion: the logic behind recycling options. Sustainability 2021;13(17):9714.
[54] Barnard E, Rubio Arias JJ, Thielemans W. Chemolytic depolymerisation of PET: a review. Green Chem 2021;23(11):3765–89.
[55] Li H, Aguirre-Villegas HA, Allen RD, Bai X, Benson CH, Beckham GT, et al. Expanding plastics recycling technologies: chemical aspects, technology status and challenges. Green Chem 2022;24(23):8899–9002.
[56] Jönsson C, Wei R, Biundo A, Landberg J, Schwarz Bour L, Pezzotti F, et al. Biocatalysis in the recycling landscape for synthetic polymers and plastics towards circular textiles. ChemSusChem 2021;14(19):4028–40.
[57] Wolf KH, Kausch M, Schröer H, Schweizer M. Fibers, 6. Polyurethane fibers. In: Ullmann's encyclopedia of industrial chemistry. Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA; 2011.
[58] Zhang S, Xu W, Du R, An W, Liu X, Xu S, et al. Selective depolymerization of PET to monomers from its waste blends and composites at ambient temperature. Chem Eng J 2023;470:144032.
[59] Zhang S, Xu W, Du R, Zhou X, Liu X, Xu S, et al. Cosolvent-promoted selective non-aqueous hydrolysis of PET wastes and facile product separation. Green Chem 2022;24(8):3284–92.
[60] Xu WH, Chen L, Zhang S, Du RC, Liu X, Xu S, et al. New insights into urethane alcoholysis enable chemical full recycling of blended fabric waste. Green Chem 2023;25(1):245–55.
[61] Van Dam JEG, Knoop JRI, Van Den Oever MJA, inventors; Stichting Wageningen Research, assignee. Method for removal of polyurethane fibres from a fabric or yarn comprising polyurethane fibres and cellulose-based fibres. International patent WO2020130825A1. 2020 Jun 25.
[62] Gong C, Zhang K, Yang C, Chen J, Zhang S, Yi C. Simple process for separation and recycling of nylon 6 and polyurethane components from waste nylon 6/polyurethane debris. Text Res J 2021;91(1–2):18–27.
[63] Johansen MB, Donslund BS, Henriksen ML, Kristensen SK, Skrydstrup T. Selective chemical disassembly of elastane fibres and polyurethane coatings in textiles. Green Chem 2023;25(24):10622–9.
[64] Grdadolnik M, Drinčić A, Oreški A, Onder OC, Utroša P, Pahovnik D, et al. Insight into chemical recycling of flexible polyurethane foams by acidolysis. ACS Sustain Chem Eng 2022;10(3):1323–32.
[65] Omrani I, Mohammadi BR. Chemical recycling of flexible polyurethane foam scraps using bio-based acidolysis agents. ACS Appl Polym Mater 2024;6 (17):10698–705.
[66] Liu B, Westman Z, Richardson K, Lim D, Stottlemyer AL, Farmer T, et al. Opportunities in closed-loop molecular recycling of end-of-life polyurethane. ACS Sustain Chem Eng 2023;11(16):6114–28.
[67] Simón D, Borreguero AM, de Lucas A, Rodríguez JF. Recycling of polyurethanes from laboratory to industry, a journey towards the sustainability. Waste Manag 2018;76:147–71.
[68] Liu B, Westman Z, Richardson K, Lim D, Stottlemyer AL, Farmer T, et al. Polyurethane foam chemical recycling: fast acidolysis with maleic acid and full recovery of polyol. ACS Sustain Chem Eng 2024;12(11):4435–43.
[69] Liu B, Westman Z, Richardson K, Lim D, Stottlemyer AL, Gillis P, et al. Vapor-phase dicarboxylic acids and anhydrides drive depolymerization of polyurethanes. ACS Macro Lett 2024;13(4):435–9.
[70] Westman Z, Perikala M, Wu X, Richardson K, Letko CS, Vlcek V, et al. Polyurethane foam acidolysis with carboxylic acids: acid structure dictates N-containing product distribution and kinetics. Polym Chem 2024;15(46):4741–52.
[71] Mahmud R, Moni SM, High K, Carbajales-Dale M. Integration of techno-economic analysis and life cycle assessment for sustainable process design—a review. J Clean Prod 2021;317:128247.
[72] Kousemaker TM, Jonker GH, Vakis AI. LCA practices of plastics and their recycling: a critical review. Appl Sci 2021;11(8):3305.
[73] Pillich M, Bargiacchi E, Bosetti L, Bardow A. D7.2. Report on the preliminary results of LCA analysis on PUR recycling. Report. Zürich: ETH Zurich; 2024.
[74] Pillich M, Schilling J, Bosetti L, Bardow A. What to do with polyurethane waste? The environmental potential of chemically recycling polyurethane rigid foam. Green Chem 2024;26(21):10893–906.
[75] Marson A, Masiero M, Modesti M, Scipioni A, Manzardo A. Life cycle assessment of polyurethane foams from polyols obtained through chemical recycling. ACS Omega 2021;6(2):1718–24.
[76] McKay T. Recycling flexible polyurethane foam via chemical recovery versus incineration for energy: a comparison of environmental and economic impacts [dissertation]. Cambridge: Harvard Extension School; 2019.
[77] Wieczorek K, Bukowski P, Stawiński K, Ryłko I. Recycling of polyurethane foams via glycolysis: a review. Materials 2024;17(18):4617.