# Chemical Recycling of Polyester Wastes *via* Catalysts Promoting Alcoholysis for Valuable Chemicals in Wood-based Structural Material Applications—A Critical Review

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Due to the societal appeal in carbon emission reduction and neutralization, chemical recycling of waste polyester for valuable chemicals has attracted attention in an increasing number of applications. Research on chemical recycling of polyester wastes is currently rising sharply and becoming a hot spot gradually. Many technical and fundamental questions still need to be addressed, such as harsh depolymerization conditions (high temperature, long reaction time, low yields, *etc.*) and techno-economy and environmental sustainability matters. The chemical recycling protocol and optimization of degradable polyester wastes are systemically investigated along with short discussions on non-degradable ones. The thermoset polyurethane and epoxy adhesives derived from depolymerized waste polyesters for contributing to wood-based structural composite materials (*e.g.*, laminated plywood, fire retarded wood coating, and transparent wood composites) along with life-cycle assessment and techno-economic analysis are also critically evaluated and analyzed. These novel insights are expect to open a new avenue to develop wood-based structural materials *via* value-added chemicals from polyester waste recycling, which contribute to the sustainable society along with prompting further research and extension in forestry biomaterials and renewable natural resources.

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## INTRODUCTION

Considering the current global plastic crisis, the annual plastic waste is projected to exceed 1 billion tons by 2060, and polyethylene terephthalate (PET) polyester waste accounts for around 12% (Li *et al.* 2025; Gao *et al.* 2025). Thus, chemical recycling of polyester waste is becoming a hot topic. Additionally, due to the societal appeal of carbon emission reduction and neutralization, the chemical recycling of polyester waste to obtain valuable chemicals in sustainable applications has attracted significant interest (Fang *et al.* 2024; Lahive *et al.* 2025). However, chemical recycling of polyester wastes currently faces many challenges, such as harsh depolymerization conditions (high temperature, long reaction time, low yields, *etc.*) and techno-economy and environmental sustainability matters (Curley *et al.* 2025; Millucci *et al.* 2025). Although a few reviews have considered

chemical recycling of *non*-degradable polyester wastes and closed-loop chemical recycling of synthetic polyester (*e.g.*, polyethylene terephthalate PET and polycarbonate PC, *etc.*) *via* metal- and/or organo- catalysts (Enking *et al.* 2025; Jia *et al.* 2023; Luo *et al.* 2024; Zhao *et al.* 2024; Xu *et al.* 2025; Mittal *et al.* 2025), research on the degradable polyester is in its infancy (Li *et al.* 2024; Yang *et al.* 2022). This review focuses primarily on the chemical recycling of degradable polyester wastes *via* catalysts that enhance alcoholysis. The non-degradable polyester wastes are briefly reviewed, given the fact that the associated chemical recycling technique is relatively mature and already evaluated by pioneer scholars. Additionally, the valuable chemicals derived from waste polyester alcoholysis are ideal building blocks for synthetic thermoset resin adhesives *via* step growth polymerization and ring-opening polymerization, which has potential for adhesive and coating applications on the wood-based advanced structural materials as alternatives to non-environmentally friendly urea-formaldehyde and phenol-formaldehyde thermoset adhesives.

According to the Google Scholar search, only few reviews in terms of "*chemical recycling biodegradable polyester*" have been reported (Feghali *et al.* 2020; McKeown *et al.* 2020; Majgaonkar *et al.* 2021; Yang *et al.* 2022; Shi *et al.* 2024; Li *et al.* 2025). Most of these previous publications are mainly focused on the general introduction of polyester depolymerization/chemical recycling approaches, while the present review emphasizes the waste degradable polyester and chemical recycling *via* catalysts promoting alcoholysis. This is instead of other methods, such as hydrolysis and aminolysis or depolymerization *via* external stimulus (photo and electricity, *etc.*). Additionally, no review work has been reported on transforming the depolymerized polyester waste into valuable chemicals for wood-based structural material applications. This review will be elucidated in the following ways: Waste degradable polyesters in terms of depolymerization conditions and protocol optimizations are systemically summarized, and then different synthetic thermoset resins with building blocks derived from depolymerized waste polyesters *via* alcoholysis chemical recycling are discussed. Thermoset resins contributing to wood-based structural composite material applications and sustainable assessments are finally summarized in order to light the way for further research and extensions in renewable natural resources and forestry biomaterials.

## VALUABLE CHEMICALS FROM CHEMICAL RECYCLING OF POLYESTER WASTES

### Chemical Recycling of PLA Polyester Wastes

Polylactic acid (PLA) has been synthesized primarily from lactic acid *via* ring opening polymerization. It has unique properties, such as compostability and biological compatibility, and has promising applications such as food packaging, agricultural mulch films, and biomedical materials, *etc*. However, its degradation completely in the natural environment requires many years (Sombatsompop *et al.* 2021). Additionally, PLA cannot degrade completely in the ocean, and these debris as microplastics and nano-plastics in seawaters threaten human health and the environment. Therefore, chemical recycling of waste PLA is needed. Compared to hydrolysis and aminolysis approaches with strong acids or bases resulting in obvious equipment corrosion (Millucci *et al.* 2025), chemical recycling of waste PLA *via* alcoholysis has attracted significant interest (Luo *et al.* 2024).

The general reaction mechanism of alcoholic depolymerization of PLA is explained as follows: an alkoxide as a nucleophile attacks the carbonyl group of ester backbone in the PLA and then produces valuable lactate esters or related oligomers (Odian 2007; Solomons and Fryhle 2011). The typical alcohol nucleophile in the alcoholysis of the PLA is methanol, ethanol, or ethylene glycol. Additionally, to introduce functional groups in the further polymerization (*e.g.*, ring opening metathesis and acyclic diene metathesis polymerization), modified alcohols (*e.g.,* allylic alcohol and 2-chloroethanol) are sometimes employed in PLA depolymerization (Leibfarth *et al.* 2012; Saito *et al.* 2022). The extent of the depolymerization reaction primarily depends on the strength of the nucleophiles and catalysts. Studies related to the chemical recycling of waste PLA *via* catalysts promoting alcoholysis are summarized in Table 1.

Metal catalysts are widely employed in waste PLA chemical recycling. The catalysts containing magnesium, calcium, and zinc elements usually have good catalytic effects in the alcoholysis of PLA. For instance, magnesium and calcium alkoxides were shown to catalyze alcoholysis of waste PLA under the reaction conditions of 120 to 180 ℃ and 1 h, and the degree of conversion reached more than 90% (Spicer *et al.* 2024). Mild depolymerization conditions along with the use of conventional yet eco-friendly synergistic or complex metal catalysts and a low-boiling solvent are highly desirable to produce ethyl lactate as a means to further optimize its depolymerization conditions. For instance, ethylene glycol as a low boiling point solvent along with various metal catalysts (*e.g.*, tetrabutyl orthotitanate, metal salt/organobase dual catalysts, and stannous octoate) has been studied relative to the alcoholysis of PLA under different reaction conditions (Majgaonkar *et al.* 2021). Alcohol and ethylene glycol as nucleophiles have some limitations. Methanol has a simple and unique structure, and it works as a strong nucleophile in the methanolysis of waste PLA, thereby inducing a decent degree of conversion. For instance, tin(II) 2-ethylhexanoate [Sn $(Oct)_2$] with the loading at 1 wt.% catalyzed the depolymerization of PLA in methanol with conversion at more than 90% (Hofmann *et al.* 2020). However, metal catalysts have some challenges in their separation from the depolymerized lactate esters (Solomons and Fryhle 2011; Odian 2007; Hiemenz and Lodge 2007). Searching for environmentally friendly catalysts is highly desirable.

Ionic liquids and deep eutectic solvents (DESs) as benign catalysts have attracted significant interest. Ionic liquids as "melting salts" are composed of negative and positive ions. They exist in liquid form under relatively low temperature conditions. DESs as the derivatives of ionic liquids are made of compounds as hydrogen donators and accepters. Ionic liquids and DESs have good solubilization capabilities for organic substances, excellent thermal stability, and reproducibility, which are promising environmentally friendly catalysts for PLA alcoholysis. For instance, ionic liquid and/or its complex have been studied for waste PLA depolymerization, and the product conversion percentages of 85 to 90% have been reached (Liu *et al.* 2018; Hubble *et al.* 2023). ChCl and $ZnCl_2$ as DESs catalysts have been used to recycle PLA *via* methanolysis, and the conversion reaches 98.3% at 3 h and 120 °C (Zhu *et al.* 2024). However, most ionic liquid and DESs catalysis have issues in terms of catalyst separation and recycling. To tackle these matters, organocatalysts have been used for PLA alcoholysis.

**Table 1.** Depolymerization of Waste/End-of-Life Degradable PLA *via* Alcoholysis

| Material | Catalysts | Solvent | Time (h) | Temperature (°C) | Conversion or Yield (%) | Literature |
|---|---|---|---|---|---|---|
| PLA | Tetrabutyl orthotitanate | EG/PDO/BDO | 1/6 | 240 | 65, 90 | Nim *et al.* (2020) |
| PLA | Stannous octoate | EG | 1 | 190 | NA | Luo *et al.* (2024) |
| PLA | $Zn\{(R,R)\text{-}DMEG_2\text{-}(1,2)ch\}_2$ | Methanol | 2 | 60 | 80-90 | Liu *et al.* (2024) |
| PLA | MHMDS | Methanol | 2/60 | R.T. | >90 | Liu *et al.* (2024) |
| PLA | Titanium (IV) butoxide | PG | 3 | 188 | 80-85 | Figalla *et al.* (2024) |
| PLA | Catalyst free | Methanol | 6 | 140 | >90 | Zhang *et al.* (2024) |
| PLA | [HTBD][OdmGly] ionic liquids | Methanol | 3 | 70 | ~93 | Hubble *et al.* (2023) |
| PLA | Zn (II) complex | Methanol | 1 or 4 | 70-110 | >94 | Román-Ramírez *et al.* (2020) |
| PLA | $Zn(HMDS)_2$ | Methanol | 2 | R.T. | 98 | Yang *et al.* (2022) |
| PLA | $[Ph_3C][B(C_6F_5)_4]$ | Methanol | 1 | 120 | 100 | Wang *et al.* (2025) |
| PLA | Sodium hydroxides | Methanol | 1/6 | 30 | >80 | Chen *et al.* (2025) |
| PLA | Imidazole-anion-derived ionic liquids | Methanol | 1 | 70 | 87 | Liu *et al.* (2018) |
| PLA | Magnesium | Methanol | 1 | 160 | >90 | Petrus *et al.* (2018) |
| PLA | Metal salt and organobase dual catalysts | EG | 2 | 120/150/180 | >90 | Spicer *et al.* (2024) |
| PLA | Deep eutectic solvents | Methanol | 3 | 120 | >80 | Zhu *et al.* (2024) |

Note: ethylene glycol (EG), butane-1,4-diol (BDO), propane-1,3-diol (PDO), propylene glycol (PG) and dimethyl (or diethyl) carbonate (DMC); room temperature (R.T.); M[bis(trimethylsilyl)amide] (MHMDS, M = Li, Na, K); Mixture of N,N-dimethyl-glycine and 1,5,7-triazabicyclo[4.4.0]dec-5-ene ([HTBD][OdmGly]); Zinc bis[bis(trimethylsilyl)amide] ($Zn(HMDS)_2$)

**Table 2.** Depolymerization of Waste Degradable PHA *via* Alcoholysis and Hydrolysis

| Material | Catalysts | Solvent | Time (h) | Temperature (°C) | Conversion or Yield (%) | Literature |
|---|---|---|---|---|---|---|
| PHB | p-toluenesulfonic acid | Water | 12 | 180 | 70-90 | Gabirondo *et al.* (2025) |
| PHBV | Taurine | Water | 12 | 180 | 88 | Gabirondo *et al.* (2025) |
| PHB | Fe-containing magnetic ionic liquids | Methanol | 3 | 110-140 | 70-90 | Song *et al.* (2019) |
| PHB | $[MIMPS]FeCl_4$ | Methanol | 3 | 140 | ~87 | Song *et al.* (2018) |
| PHB | para-toluensulphonic acid | Methanol | 2 | 151 | ~92 | Jašek *et al.* (2022) |
| PHB | Acidic functionalized ionic liquids | Methanol | 3 | 140 | 70-90 | Song *et al.* (2016) |
| PHB | Ferric chloride | Methanol | 1-4 | 130-150 | 70-90 | Song *et al.* (2018) |
| PHB | $Zn(HMDS)_2$ | n-Butanol | 1.5-5 | 70-110 | >90 | Wang *et al.* (2023) |

Note: 1-(3-sulfonic acid)-propyl-3-methylimidazole ferric chloride ($[MIMPS]FeCl_4$)

Organocatalysts were initially studied in catalyzed polyester synthesis *via* ring opening polymerization and depolymerization with a closed-loop approach (Saito *et al.* 2018; Deacy *et al.* 2021; Lin *et al.* 2018; Li *et al.* 2024; Chen *et al.* 2022; Yuan *et al.* 2019). Due to the good catalytic effect of organic bases or Lewis acids in controlled ring-opening polymerization of PLA synthesis, a few successful studies have been carried out on the methanolysis of PLA chemical recycling to achieve a yield at more than 90%, without catalyst separation and metal catalyst debris problems (Figalla *et al.* 2024; Xie *et al.* 2024; Wang *et al.* 2025). Therefore, organocatalysts can be regarded as the new stars in alcoholysis of PLA waste. However, most of the work has been carried out at lab scale for PLA chemical recycling. Pilot-scale chemical recycling *via* organocatalyst is highly desirable. Fortunately, diphenyl phosphate catalyzed hydrolysis of PLA has been demonstrated at the pilot scale recently (Wu *et al.* 2024). Additionally, compared to chemical recycling of single PLA waste, mixed PLA-containing waste poses huge challenges. Fortunately, the chemical recycling of mixtures has benefitted from large improvements over the most recent two years. For instance, one study achieved selective recycling as an exciting milestone currently with fast and mild depolymerization conditions (Liu *et al.* 2024).

## Chemical Recycling of PHA Polyester Wastes

As a relatively new biodegradable polymer, polyhydroxyalkanoate (PHA) has attracted attention for bioplastic and sustainable packaging along with biomedical areas (Tu *et al.* 2022). The PHA family primarily includes poly (3-hydroxyvalerate), poly(hydroxybutyrate) (PHB), and poly(hydroxybutyrate-co-valerate) (PHBV). As a primary member of PHAs, PHB homopolymer has been the most studied, as it has the potential to be synthesized within microorganisms without requiring further modification. However, PHB has inherent drawbacks as a polymer for packaging, namely brittleness and low toughness. Copolymerization of PHB with a 3-hydroxyvalerate comonomer, PHBV has been proposed to achieve better processability, higher ductility, and better impact properties. Research in terms of waste PHA recycling is still in infancy currently, and most work has focused on mechanical recycling (Dedieua *et al.* 2022; Belyamani *et al.* 2025). Chemical recycling of PHA has involved a few trials. A summary of waste PHA chemical recycling *via* alcoholysis is listed in Table 2. For instance, waste PHB chemical recycling was investigated *via* ionic liquids or their derivatives as catalysts under diverse temperature and time conditions, and the conversions were between 70 and 100%. Compared to PHB chemical recycling, as another family member of PHA, PHBV chemical recycling, has been rarely reported. One case study employed metal catalyst taurine achieved the conversion of PHBV at 88% under relative mild depolymerization conditions, *e.g.*, 180 ºC and 12 h (Garbirondo *et al.* 2025). Organocatalyst as an environmentally friendly catalyst is highly desirable in PHA chemical recycling as it has been extensively employed in catalyzed synthesis of PHA recently (Saito *et al.* 2018; Deacy *et al.* 2021). However, almost no research has been reported on the organocatalyzed waste PHA chemical recycling.

Polybutylene adipate terephthalate (PBAT), polybutylene succinates (PBS), and polycaprolactone (PCL) as other common degradable polymers have applications widely such as shopping bags, packaging sheets, agricultural films, and biomedical materials. Table 3 lists methods for the chemical recycling of these degradable polyesters.

**Table 3.** Depolymerization of Other Waste Degradable Polyesters *via* Alcoholysis and Hydrolysis

| Material | Catalyst | Solvent | Time (h) | Temperature (°C) | Conversion or Yield (%) | Literature |
|---|---|---|---|---|---|---|
| PBAT | Adipic acid | Water | 8 | 170 | ~75 | *Zheng et al.* (2024) |
| PBAT | Tin-based catalysts | Methanol | 7 | 140 | 30-50 | *Parodi et al.* (2023) |
| PBS | Succinic acid | Water | 5 | 150 | 100 | Zheng *et al.* (2024) |
| PCL | $Zn(OAc)_2$ | Methanol | 10 | 160 | 40-80 | Cheung *et al.* (2021) |
| PCL | TBD | Methanol | 1-3 | 80 | >90 | Dong *et al.* (2022) |

Note: 1,5,7-triazabicyclo [4,4,0] dec-5-ene (TBD)

**Table 4.** Depolymerization of Waste/End-of-Life PET and PC *via* Alcoholysis

| Material | Catalyst | Solvent | Time (h) | Temperature (°C ) | Conversion or Yield (%) | Literature |
|---|---|---|---|---|---|---|
| PET | Antimony (III) oxide or Zinc acetate | EG | 1/12-5/12 | 240 | >90 | Mohammadi *et al.* (2020) |
| PET | $CaCO_3$/CaO/$TiO_2$ | EG | 1.5 | 200 | ~95 | Enayati *et al.* (2024) |
| PET | Organocatalyst $Et_3N$ | Methanol | 2 | 200 | 88 | Muangmeesri *et al.* (2024) |
| PET | TBD | EG | 1/4 | 100 | >90 | Olazabal *et al.* (2024) |
| PET | Amino acid-based cholinium ionic liquids | EG | 6 | 150 | 51 | Marullo *et al.* (2021) |
| PC | DBU/DMAP | EG | 24 | 80 | >95 | Edge *et al.* (2025) |

Note: Calcium carbonate ($CaCO_3$), calcium oxide (CaO), and titanium dioxide ($TiO_2$); 1,8-diazabicyclo [5.4.0] undec-7-ene (DBU) and 4-(dimethyl amino) pyridine (DMAP) *via* continuous flow conditions

As it is widely used in agricultural films, PBAT chemical recycling has been intensively studied recently. For example, water as the hydrolysis solvent has been carried out, due to its capability of achieving depolymerization under relatively high temperature (Zheng *et al.* 2024). Tin-based catalysts with methanolysis depolymerization of PBAT were further explored for its depolymerization in relatively mild conditions (Parodi *et al.* 2023).

A few studies have examined PBS chemical recycling. However, it was carried out with harsh alkali solutions, and the conversion was not satisfactory. The yield was slightly more than 50% with long time at 48 h (Zheng *et al.* 2024). Future studies should investigate PBS chemical recycling with advanced catalyst approaches. Alternatively, waste PCL depolymerization with organocatalyst 1,5,7-triazabicyclo 4.4.0 dec-5-ene (TBD) *via* methanolysis has been studied with relatively mild conditions (Dong *et al.* 2022). Organocatalyst is an environmentally friendly, economic and promising approach for PCL waste chemical recycling compared to the metal catalyst, enhancing its methanolysis (Cheung *et al.* 2021). Such an approach can possibly be applied for the depolymerization of waste polyglycolic acid, another degradable polyester, which is not widely focused on currently. Chemical recycling of non-degradable polyester waste is another important task currently.

### Chemical Recycling of Non-Degradable Polyester Wastes

PET is the most widely used polyester, and it is used in such plastic items as bottles and fabrics. As PET is not degradable in nature (de Carvalho *et al.* 2025), its chemical recycling research was initialized early compared to degradable PLA, PBAT, and PHA. As the research on chemical recycling of PET waste is relatively mature, this review primarily discusses typical cases. For more studies, please refer to a recent review paper (Tan *et al.* 2025). Herein, the typical technology in terms of its chemical recycling *via* alcoholysis is introduced shortly in Table 4. For example, the PET alcoholysis under metal catalyst was initially studied under harsh conditions, *e.g.*, 240 °C, for which its conversion is great, at almost 100% (Mohammadi *et al.* 2020). The chemical recycling at relatively mild conditions (15 min and 100 °C) *via* organocatalyst was also carried out, and the conversion could reach more than 90% (Olazabal *et al.* 2024). In another chemical recycling trial with $Net_3$ catalyst under methanolysis, the conversion reached 90% (Muangmeesri *et al.* 2024).

As another non-degradable polyester, polycarbonate (PC) is an important engineering plastic. With unique properties, such as robust mechanical properties and excellent thermal resistance, PC is widely used in many fields, such as automotives and aerospace. Chemical recycling of these end-of-life PC materials has also been studied (Qin *et al.* 2024; Wu *et al.* 2025). However, the alcoholysis of waste PC chemical recycling approach is relatively new (Padhi *et al.* 2024; Edge *et al.* 2025), and there is a need for future studies.

## SYNTHETIC THERMOSET RESINS FOR ADHESIVES AND FUNCTIONAL COATING BY UPCYCLING MONOMERS, OLIGOMERS, OR MACROMOLECULES OF POLYESTER WASTES AND LIGNIN EXTRACTED FROM WOOD

Chemical recycling offers opportunities to upcycle waste polyesters into valuable monomers and oligomers or macromolecules (Gupta *et al.* 2025). These valuable products derived from chemical recycling of waste polyesters are unique raw materials for thermoset

synthesis toward wood adhesive and coating applications. As a suitable end-of-life solution, this approach decreases the dependence on raw petroleum-based materials for producing thermosets, polyurethane, polyurea, epoxy and cross-linked polyacrylic resins.

## Conventional Polyurethane/Polyurea Resins

Polyurethane and polyurea have excellent flexible and outstanding chemical resistance, which are the prevalent choices in adhesives and coating applications (Senra *et al.* 2023). Polyurethane or polyurea is usually synthesized *via* polyols or polyamine and diisocyanates with or without catalyst. It sounds like a sustainable approach to the synthetic polyurethane from polyols *via* chemical recycling of waste PET. However, few studies of synthetic polyurethane and polyurea with chemical recycling of waste polyesters have been carried out, as the waste polyester chemical recycling is in its infancy. As a typical case, the polyols were prepared *via* the oligo-esters by waste PET glycolysis and aromatic/aliphatic diacids and then reacted with diisocyanates to produce polyurethane (Pu *et al.* 2024). As another example, a one-step conversion of bisphenol A-based polycarbonate to produce valuable-added diols with varying chain lengths was investigated. The resulting polyols were subsequently utilized as soft segments in combination with 4,4'-methylene diphenyl diisocyanate in the production of polyurethanes as potential for wood adhesive applications in Fig. 1 (Godinho *et al.* 2021; Saito *et al.* 2025).

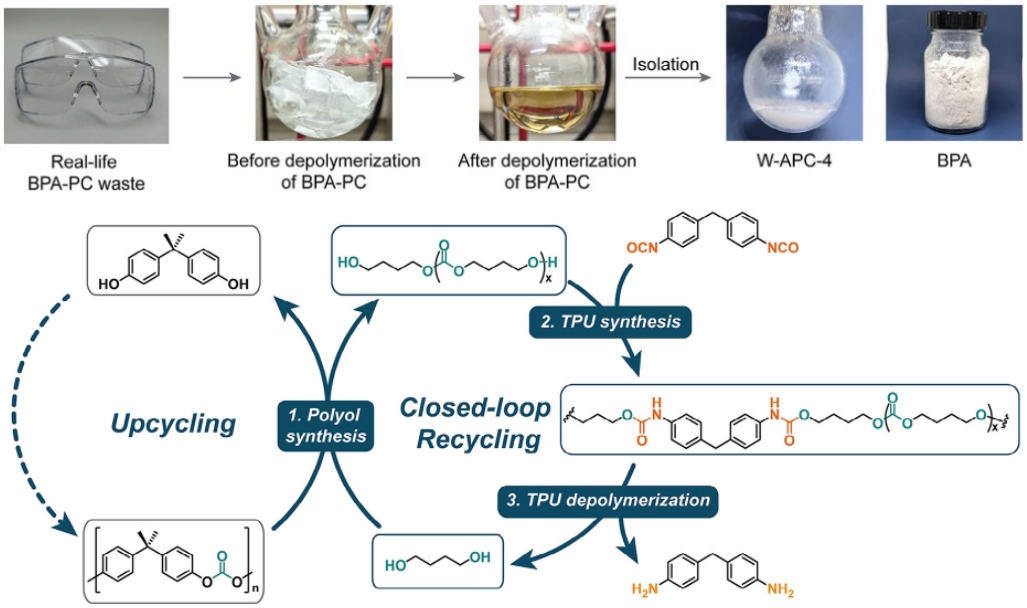


**Fig. 1.** PC alcoholysis chemical recycling and utilization of recycled valuable chemicals in synthetic polyurethanes (Saito *et al.* 2025). Figure republished with permission from Wiley Publishing Co.

## Conventional Epoxy Resins

As another classical thermoset for adhesive and coating applications, epoxy is usually prepared by a diamine curing agent and prepolymer *via* the condensation polymerization of bisphenol A and epichlorohydrin. Due to their excellent adhesive strength and thermal stability, recycled PET derived chemicals are ideal building blocks to produce epoxy resins for coating and adhesive applications. For instance, α, ω-dicarboxylic acid oligo (ethylene succinate-co-terephthalate) and terephthalic acid as the valuable added oligomer and small molecule were produced from the chemical recycling of waste PET

and then worked as the curing agent to prepare epoxy resins (Hoang *et al.* 2022). Currently, research on waste PLA and PHA chemical recycling for epoxy resin synthesis is rare, as the chemical recycling technology of waste PLA and PHA degradable polyesters are at their early stages (Liu *et al.* 2024; Luo *et al.* 2024; Yang *et al.* 2022; Lehnertz *et al.* 2022). However, the upcycling value-added products from waste PLA and PHA contributing to epoxy and PU resin synthesis will be continuously increasing (Nim *et al.* 2023; Cheng *et al.* 2025).

### Dynamic Covalent Crosslinked Epoxy and PU Resins

Compared to the conventional covalent cross-linked epoxy and PU resin adhesives, development of dynamic covalent cross-linked epoxy and PU vitrimer resins as reworkable adhesives and coatings in wood-based structural material are promising to deal with their end-of-life challenges. For instance, PET waste was upcycled to produce closed-loop recyclable vitrimer plastics. To be more specific, catalyst- and solvent-free chemical recycling provided a direct approach to deconstruct PET waste into vitrimer building blocks from mixed PET sources. The readily available Jeffamine T403 was used for the depolymerization of PET waste to form a nucleophilic, tetraamine macromonomer, and then reacted with diacetoacetates to form dynamic covalent vinylogous urethane linkages. The resulting vitrimer materials exhibited closed-loop chemical recyclability (Danielson *et al.* 2025). This work opens a new avenue to design dynamic covalent bonded thermosets from chemical recycling of waste polyesters, such as PLA and PHA. As another example, oligomers depolymerized from PET *via* glycerol alcoholysis were studied for the preparation of vitrimer materials (Wei *et al.* 2023). In addition to using valuable chemicals from chemical recycling of polyester, the renewable natural sources derived from wood products (*e.g.*, lignin) are desirable for building blocks in the synthetic PU and epoxy vitrimer resins (Saito *et al.* 2022; Comí *et al.* 2025; Sun *et al.* 2025). Such resins have potential for wood adhesives.

## WOOD-BASED ADVANCED STRUCTURAL MATERIALS *VIA* UPCYCLING CHEMICALS DERIVED ADHESIVES AND COATINGS

### Adhesive in Lumbers, Plywood, and Particle Boards

Wood-based structural materials have wide applications in North America, such as construction (wooden structures, beams, and walls) and indoor furniture products (tables, chairs, wardrobes, and bookcases). According to the data from 2020 to 2022, North America utilized wood-based structure materials at a volumetric rate of over 20 million $m^3$/year (Garcia *et al.* 2024). Lumber is primarily produced as a solid product sawn from logs, while plywood and oriented strand board are two major types of wood-based structural materials made of adhesive-bonded wood veneers and wood fibers/flakes, as shown in Fig. 2.

Over two-thirds of the manufacturing process of wooden products require adhesives to form strong chemical bonds between wood fibers, ensuring that the wood is connected stably and securely at the adhesive joints for enhancing the overall performance and adding value to wooden products (Gonçalves *et al.* 2021). Thermosetting resin phenol-formaldehyde synthetic *via* condensation polymerization of phenol and formaldehyde using acid or base catalyst are the most used wood adhesives along with urea-formaldehyde and melamine-formaldehyde thermoset resins due to their low-cost and strong bond

strength performance in both dry and wet environmental conditions (Odian *et al.* 2007). However, these thermosets tend to release formaldehyde and other harmful gases, posing a risk to human health (Wang *et al.* 2017; Bansode *et al.* 2021). The development of environmentally friendly formaldehyde-free adhesives is attracting attention. Renewable resources-based wood adhesives attracted extensive studies, such as, cellulose, lignin or soy protein adhesives (Huzyan *et al.* 2021; Neitzel *et al.* 2023; Ghahri *et al.* 2025). However, the development of environmentally friendly adhesives at the cost of intrinsic bond strengths in conventional thermoset adhesives can't meet the requirements for real wood construction application due to the potential safety considerations (Wang *et al.* 2020; Peng *et al.* 2023; Chen *et al.* 2024). Epoxy and polyurethane or polyurea thermosets are ideal alternatives to urea-formaldehyde and phenol-formaldehyde as wooden adhesives, as they have comparative mechanical properties without toxic gas release issues. Additionally, it is a feasible strategy to preserve the advantages of conventional thermoset wood adhesives and introduce the new building units in conventionally synthetic epoxy and polyurethane or polyurea resins by borrowing value-added chemicals from chemical recycling of waste polyesters. This approach can make sense, given the current energy shortage crisis and growing environmental awareness of people. For instance, the diols from glycolysis waste PET can be used as polyols, chain extenders of PU synthesis (Pu *et al.* 2024).


**Fig. 2.** Wood veneers were cut from timber and plywood produced from wood veneers *via* hot press (Hoadley 2000; Chen *et al.* 2024). Figure republished with permission from Hoadley (2000); Copyright 2024, American Chemical Society

**Table 5.** Environmentally Friendly PU and Epoxy-based Wood Adhesives from Waste Polyester Depolymerization

| Adhesives | Wet SS (MPa) | Dry SS (MPa) | Test Standard | Literature |
|---|---|---|---|---|
| PUU | NA | 10.9 | DINEN302−1 | Thoma *et al.* (2024) |
| PU | NA | 1.6 | ASTM D1002 | Pu *et al.* (2024) |
| PU | 7.4 | 11.7 | ASTM D 2339-98 | Phetphaisit *et al.* (2013) |
| Epoxy | 1.7 | 1.8 | ANSI/HPVA HP-1-2000 | Mousavi *et al.* (2019) |

Note: Shear strength, SS; poly(urethane urea) (PUU)

However, the research on PU or epoxy resins from chemical recycling of waste polyesters for wood adhesives is still in its infancy. For instance, the synthesis approach involved an NCO-terminated prepolymer formed by polypropylene glycol and isophorone diisocyanate followed by introducing recycling PET for a chain extension reaction to rapid cross-linking and expansion of PU chain segments (Pu *et al.* 2024). The PU adhesives synthetic from chemical recycling of waste polyesters are listed in Table 5. For instance, the PU adhesives were prepared from hydroxyl liquid natural rubbers and modified chemical recycled PET. It is worth noting that the glycolysis of PET waste was used as the chain extension for PU synthesis (Phetphaisit *et al.* 2013). Waterborne polyurethane provides an option for wooden adhesives, besides conventional PU. As the primary chemical constitutes conventional waterborne polyurethane formulations, the synthesis of $CO_2$-based polyols *via* $CO_2$ and propylene oxide copolymerization offers a dual carbon management strategy in addition to toxic isocyanate chemical alternatives. For instance, the lignin-based waterborne polyurethane adhesive exhibited superior bonding performance, and this adhesive also demonstrated closed-loop recyclability *via* ethanol dissolution (Li *et al.* 2025). In addition to PU adhesives, epoxy and polyacrylic-based adhesives work for wood-based composites. For instance, epoxy resins made of bisphenol A diglycidyl ether, polyamidoamine, and polyethylenimine were studied as plywood adhesives (Mousavi *et al.* 2019). To replace toxic BPA in environmentally friendly adhesives for wood, lignin is an ideal alternative in epoxy adhesives for future studies. Except for PU and epoxy adhesives, hydroxyl-functional polyacrylic polymers cross-linked by the polysilazane have been investigated as wood adhesives (Chatterjee *et al.* 2025).

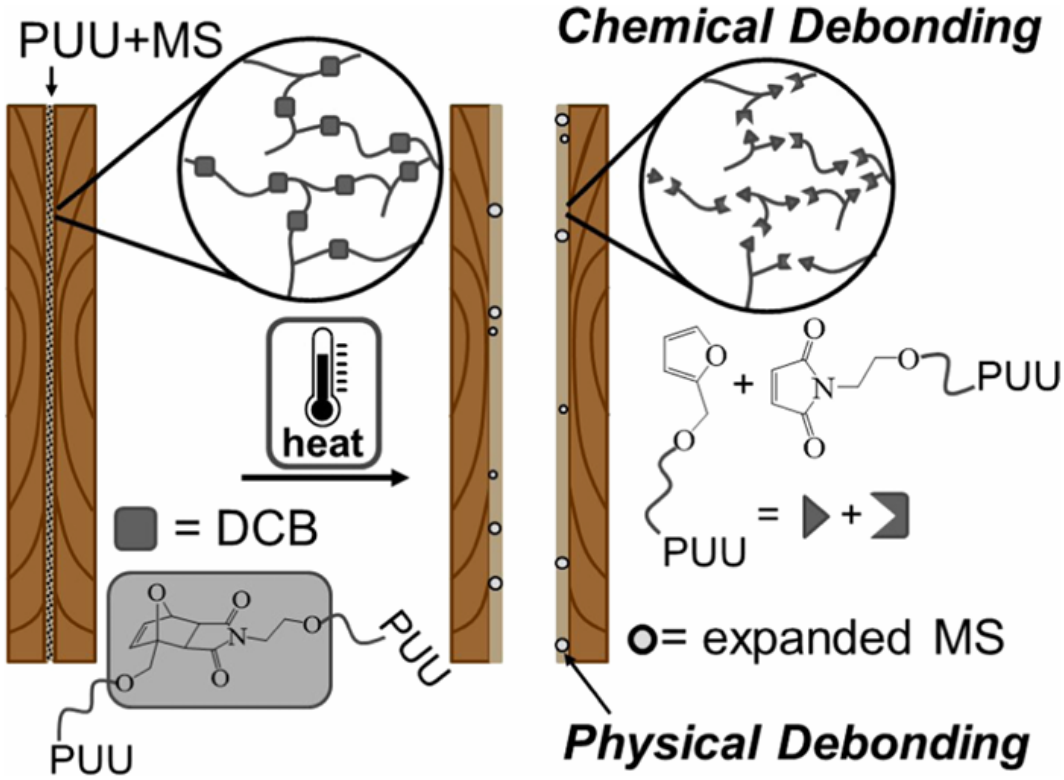


**Fig. 3.** Dynamic covalent bonded synthetic PUU as reworkable and recyclable wood adhesives (Thoma *et al.* 2024). Copyright 2024, American Chemical Society, CC-BY 4.0.

However, conventional thermosets with covalently chemical bonding adhesion are difficult to restore when the bonding interface is damaged or fractured, which reduces the service life of wooden products (Lian *et al.* 2025; Thoma *et al.* 2024). The thermoset adhesives with dynamic covalent bonds to replace the default covalent bonds make it possible to address the dilemma in dealing with end-of-life wooden products, such as poly(urethane urea) adhesives with dynamic covalent bonds of furan and maleimide in Fig. 3 (Thoma *et al.* 2024). For instance, a thermoplastic hyperbranched polyurethane adhesive with a polyurethane prepolymer and lipoic acid with S-S bonds as the terminal groups were designed as wood adhesive with the ability to bond repeatedly. Under heating conditions, the dynamic exchange of S-S bonds occurs on both sides of the damaged interface, leading to reformation of the polymer network structure on both sides of the break and restoration of the adhesive strength (Zhou *et al.* 2025).

## Functional Coating in Fire Retardancy and Moisture Stability along with Early Fire Alarm Warning of Lumbers, Plywood, and Particle Boards

Wood-based structural materials have fire retardancy and moisture stability issues, which restrict their broad applications (Gašparík *et al.* 2017; Hosseinashrafi *et al.* 2023). Especially, enhancing fire retardancy of wood-based structural composites is a long-term and tough question. The conventional way is by infusing fire additive particles into wood substrates. However, this approach has its intrinsic issues. Fire resistance often is achieved at the cost of other properties, such as mechanical properties. As an alternative approach, fire retarding wood-based structural materials can be achieved *via* surface coating of epoxy or PU; such an approach has been used to design fire retarding wood composites (Jin *et al.* 2017; Wang *et al.* 2017; Jang *et al.* 2025). In addition to the fire retarding matter, moisture stability is another practical matter of wood-based composites.

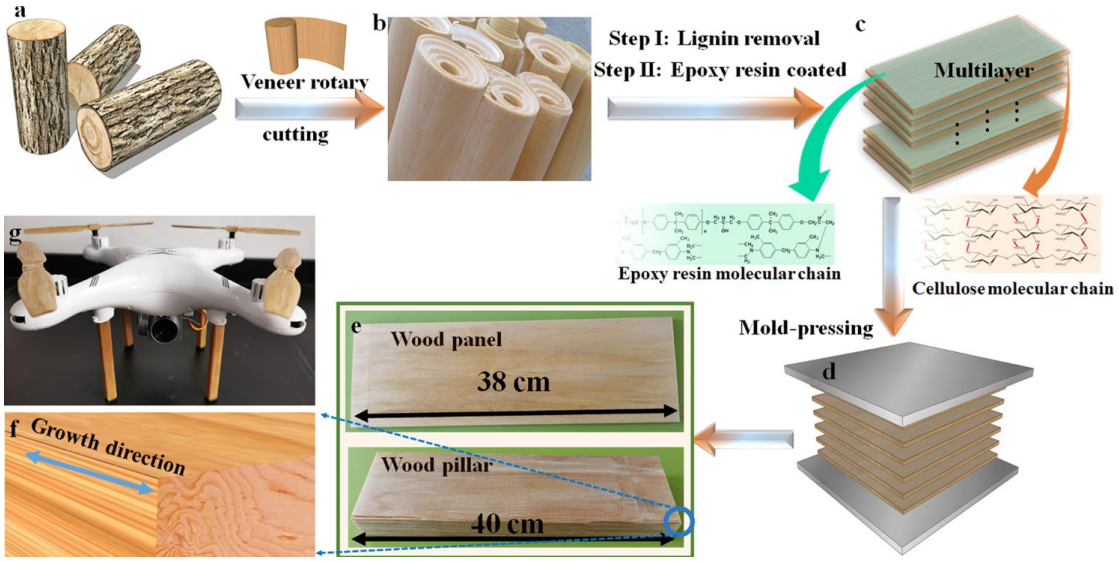


**Fig. 4.** Laminated wood composites from delignified wood veneers (Tang *et al.* 2021). Figure republished with permission from American Chemical Society.

Waterborne polyurethane based fire-resistant, and waterproof coating has been synthesized for wood protection (Hao *et al.* 2023). Polyacrylic based copolymer resin doped with organo-clays coating has been developed for plywood protection (Chuang *et al.* 2011). Additionally, epoxy resins have potential as coating on wood substrates as a

means to extend their life-times, as indicated in Fig. 4. For instance, lignin-derived epoxy resin coating has been developed for wood fire retarding protection (Liang *et al.* 2025). As another case, bio-based epoxy resin derived from phytic acid and itaconic acid as coating has been studied as fire retarding protection of rubber wood (Li *et al.* 2022; Zhang *et al.* 2025; Zuo *et al.* 2025). Except for basic wood protection, the surface coating wood-based structural materials has potential to fulfill safety protection functions such as fire alarm warning sensors (Fan *et al.* 2025). However, the research on waste polyester derived epoxy resin wood adhesives has a few studies, and it is highly desirable for further research in the future.

## Transparent Wood-based Composites

Transparent wood has gained attention recently. Owing to its unique merits, such as high optical transmittance and efficient mechanical and thermal insulation properties, transparent wood has potential for applications such as windows, ceiling, and rooftops as alternatives to plate glass in Fig. 5 (Jia *et al.* 2019; Popović *et al.* 2022; Yang *et al.* 2024). To prepare delignified transparent wood-based composites from wood veneers, wood veneers are immersed in 1 wt.% sodium chlorite under controlled reaction conditions, pH (pH 4.6) and temperature (80 °C). Next, resins with similar refractive index, *e.g.*, epoxy resin and poly(methyl methacrylate) (PMMA), are impregnated into bleached wood pores *via* vacuum (Yue *et al.* 2021; Cheng *et al.* 2022). Epoxy resins with both optical and adhesive properties are useful in the design of transparent wood-based structural composites. For instance, transparent wood was prepared *via* the bleaching process by KOH and $NaClO_2$ treatment to remove the hemicellulose and lignin effectively, and the resulting pores in woods were impregnated with epoxy resin for transparent wood composites (Cai *et al.* 2021). The transparent wood-epoxy composites also met fire retardancy requirements.


**Fig. 5.** Potential applications of transparent wood composites (de-lignin transparent wood impregnated with PMMA resin and hybrid cerium-doped zinc oxide nanorods as UV-absorbance and reflection fillers) in sustainable buildings (Yang *et al.* 2024). Figure republished with permission from American Chemical Society

The development of intrinsic fire retarding epoxy resins impregnating transparent wood composites sounds promising as an alternatives to glasses (Fan *et al.* 2022). According to our understanding, most transparent wood-based composites are primarily targeting two-dimensional applications currently, *e.g.*, windows and ceilings. By shape transformation and modifications, such technology has the potential to be extended to curved shaped windows and ceilings. Thanks for the shape memory and reworkable properties of epoxy resin vitrimer materials, the epoxy impregnating transparent wood composites have been shown to display excellent editable shape and unique optical performance (Zhang *et al.* 2020; Wang *et al.* 2022). In addition to the optical material applications, the addition of functional particles (*e.g.*, phase change materials) offer the options of transparent wood-vitrimer composites with temperature- and/or color-responsive properties (Qiu *et al.* 2020; Yang *et al.* 2024). This research field is still underdeveloped and there is a need for further research.

## Sustainable Assessments of Wood-based Structural Composites *via* Life-Cycle Analysis and Techno-Economic Assessment

Life cycle (LCA) and techno-economic (TEA) assessments are necessary for sustainability assessment of wood-based structural composite materials. Combining TEA and LCA analysis can comprehensively assess the relationship and trade-offs between economic and environmental impacts of chemically recycled waste polyester derived valuable products-based wood adhesives and commercialized urea-formaldehyde and phenol-formaldehyde adhesives in wood-based structural composite materials. As a quantitatively sustainable analysis method to evaluate the entire process of wood-based structural materials, LCA primarily involves raw material extraction, production of wood-based structural materials, their transportation, use, and waste disposals along with potential environmental impacts. Considering the toxic BPA repeat unit in epoxy and isocyanate repeat unit in polyurethane as wood adhesive, the development of lignin-derived vanillin and eugenol as alternatives to BPA in epoxy and isocyanate-free PU toward environmentally friendly wood adhesives is highly desirable, contributing to truly sustainable wood-based structural composite materials instead of "*pseudo*-sustainability" like the most published works currently. Frankly speaking, this is a tough and long road according to the world research on wood adhesives currently. Thanks for the contribution of "*Simapro*" and "*Open LCA*" software, the awkward situations are becoming alleviated regarding the arguments of "sustainability" in wood adhesives and wood-based structural materials with the evidence of real data supporting.

Regarding TEA challenges of chemically recycled waste polyesters derived valuable products-based wood adhesives in wood-based structural composites, two aspects need to be considered, namely demonstrating technological feasibility and achieving cost competitiveness with conventional adhesives. The cost of obtaining clean recycled plastic feedstock can constitute more than half of the final monomer price. Utilizing cheaper mixed waste plastic streams can mitigate some of these challenges. Although the merits of reworkable epoxy or PU adhesives contribute to the recyclable or remold wood-based structural materials, their additional synthetic protocols need to be minimized or optimized. Such tradeoffs have been shown *via* "*Aspen Plus*" software simulation and calculation to achieve cost-cutting compared to conventional wood adhesives (Yu *et al.* 2025).

## CONCLUSIONS AND FUTURE PROSPECTS

This critical review has focused on the chemical recycling of polyester wastes as a source of value-added chemicals as functional monomers to develop thermoset resins (epoxy and polyurethane, *etc*.) in wood-based advanced structure material applications (*e.g.*, thermoset adhesives and coating). Alcoholysis is emerging gradually as a powerful strategy for chemical upcycling of degradable polyester wastes. However, this process frequently encounters challenges such as low catalytic activity, poor selectivity, and difficulties in product separation. Therefore, the development of suitable catalysts with high efficiency and selectivity is imperative for future research and implementation. Additionally, the direct transesterification reaction is an attractive idea as a new approach transforming the waste PET into valuable polymers (Karanastasis *et al.* 2022; Zhang *et al.* 2023; Fang *et al.* 2024). Such an approach can be extended for vitrimer adhesives and powder coating on wood-based composites (Akkus *et al.* 2019). The direct transesterification upcycling PET approach makes it possible to convert other PBAT waste for advanced wood-based composite applications and antimicrobial and UV block functional transparent wood materials.

The design of new thermoset resin adhesives by utilizing depolymerized monomers or oligomers must incorporate considerations of chemical recyclability for contributing to the sustainability of wood-based structural composite materials. The research on transparent wood composites as the 2.0 Version of wood and plastic composites named WPCs are growing quickly, which is a promising research field for the next decade.

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