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RESEARCH ARTICLE

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Biodegradable waterborne polyurethane-urea dispersion adhesives with high biocontent

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Abstract

Non-biodegradable petroleum-based plastic wastes have become a leading environmental concern, and new efforts are underway to prepare biobased and biodegradable replacements. We have explored the preparation of adhesives suitable for use in consumer products, and here we report the development of waterborne, biodegradable adhesives from biobased monomers resulting in adhesives exceeding 70% biocontent. Using water as the polymer medium, viscosity challenges and the use of volatile organic solvents are avoided. Material properties of the polyurethane dispersions, resulting films, and laminates produced showed M_w ranging between 56,000 and 124,000. Lastly, the biodegradability of films and laminates was evaluated. The resulting metrics indicate that the adhesives produced meet the desired mechanical and biodegradability targets, indicating that high renewability content solvent-free polyurethane dispersions are a viable solution for lamination adhesives.

KEYWORDS

adhesives, biobased polymers, composite polymers, compostable, polyurethane dispersions, waterbased polymers

1 | INTRODUCTION

Polyurethanes (PUs) are a versatile class of polymers used for a variety of applications such as insulation, footwear, clothing, automotive parts, adhesives, pharmaceuticals, and coatings.[1–6] PUs have the enormous benefit of taking on the form best suited for a desired application: flexible or rigid thermoset foams, thermoplastics, solvent-based or water-based coatings.[7–10] PU formulations are fundamentally synthesized using two basic components, a polyol and polyisocyanate, both of which can vary depending on the application. When choosing the proper components for formulation of a PU product, not only physical properties must be considered, but also renewability, product end-of-life, and environmental contamination.[11] Biobased materials have come to the forefront of chemical synthesis in recent years due to consumer consciousness and the constantly fluctuating price of petroleum.[12,13] For biodegradation of PUs, polyester-polyols are ideal candidates for development of environmentally friendly polymers. Several polyester building blocks, including diacids and diols, are readily available from renewable sources.[11] These biobased polyester-polyols have been shown to produce commercially viable

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materials, with metrics comparable to petroleum-sourced products.[14,15]

For adhesive PU applications, several properties must be considered. First, PU adhesives must have low viscosities to allow for uniform adhesive application. Historically, polyether-polyols have been preferred over polyester-polyols due to their lower viscosities, allowing for easier incorporation in manufacturing.[16] However, PUs made from polyether-polyols show higher resistance to hydrolysis and biodegradation, thus they are not preferred for materials with short end-of-life applications, such as packaging.[17] PUs from polyester-polyols have been shown to biodegrade in soil, compost, and the ocean.[18–20] While the high viscosities of polyester-polyols have typically been overcome by use of volatile organic compounds (VOC) such as acetone, 1-butanone, and toluene, the adverse effects to workers and the environment have limited the commercial use of VOCs for viscosity reduction. Therefore, water-borne adhesives are becoming increasingly desirable and an important part of green manufacturing principles.[21]

Waterborne Polyurethane-urea dispersions (PUD) can offer solutions to some of these existing challenges. PUDs are similar to other PUs, as they are still composed of a polyol and polyisocyanate; but unlike traditional PUs, additional functional groups are added to the polymer backbone to allow for water dispersibility.[22] PUDs can be prepared as anionic, cationic, and non-ionic dispersions. Common dispersing agents, which can be implemented as PU chain extenders, are dimethylol propionic acid (DMPA) and *N*-methyl diethanolamine (MDEA), for anionic and cationic formulations, respectively.[22] Non-ionic dispersions usually have a water-soluble segment such as polyethylene oxide incorporated into the polymer backbone or as a pendant group. In the preparations, the anionic prepolymers are formed in minimal amounts of a water-miscible solvent, then dispersed in water, and the organic solvent is removed by vacuum. The resulting PUD is a low-viscosity dispersion, with polyurethane as the main component in water. PUDs have also shown improved properties in adhesion and flexibility when compared to solvent-borne formulations.[23–26]

This study shows that renewable and biodegradable PUDs can serve as drop-in candidates to replace existing non-biodegradable petroleum-derived adhesives. The PUDs shown here were evaluated to confirm polymer formation, dispersion stability and uniformity, adhesion strength, and biodegradability. These results show that PUDs can be prepared that perform at a similar level to commercial non-biodegradable adhesives, while providing high bio-content and end of life biodegradation. These adhesives, along with biodegradable substrates, can create fully renewable and biodegradable solutions for the drop-in replacement of commercial non-biodegradable plastics used currently, with downstream applications in multiple industries such as packaging, textiles, automotive, and furniture.

2 | EXPERIMENTAL

2.1 | Materials

Azelaic acid (AzA) was purchased from Acros Organics (Gael, Antwerp, Belgium), and succinic acid (SuA) was purchased from Visolis Inc. (Hayward, CA, USA). Dibutyltin dilaurate (DBTDL), dimethylol propionic acid (DMPA), isophorone diisocyanate (IPDI), toluene diisocyanate (TDI), triethylamine (TEA), ethylenediamine (EDA), methyl diethanolamine (MDEA), acetone, and glacial acetic acid were purchased from Sigma Aldrich (St. Louis, MO, USA). 1,3-Propanediol (PDO), and 3-methyl-1,5-pentanediol (3MPeDO) were provided by Primient Covation LLC (Loudon, TN, USA). Emerox® 14550 polyol was supplied by Emery Oleochemicals (Cincinnati, OH, USA). For acid and hydroxyl number titration acetonitrile, toluene, 2-propanol, 1-octanol, and potassium hydroxide were purchased from Fisher Scientific (Waltham, MA, USA), and P-toluenesulfonyl isocyanate (TSI) (96% purity) and 1.0 M tetrabutylammonium hydroxide in methanol were purchased from Sigma Aldrich (St. Louis, MO, USA). As a non-biodegradable Flextra Quiet® was purchased from H.B. Fuller. Acetone was dried using activated molecular sieves. All other materials were used as provided without additional purification.

2.2 | Experimental methods

2.2.1 | General procedure for synthesis of polyester-polyols

Polyols were synthesized using a three-neck round bottom flask attached to a Dean-Stark apparatus and reflux condenser to collect water byproduct. An oil bath on a hot plate stirrer is used for temperature control. Diacids and diols are added based on targeted molecular weight and placed in a constant nitrogen atmosphere. The reaction is initiated at 140°C for the first hour to allow the solids to melt and form a uniform solution. The temperature is then increased to 175°C. Once more than 80% of the water has been released, DBTDL catalyst is added, and the reaction is continued until the desired hydroxyl and acid values are reached. The hydroxyl and acid values are determined at 8-h intervals to monitor the reaction progress. Hydroxyl and acid value titrations of the polyester-polyols were performed according to ASTM 1899 and ASTM D664, respectively.

2.2.2 | General procedure for single-reactor synthesis of water dispersed polymers

The polyester-polyol is dried in a vacuum oven at 90°C for 24 h before polyurethane synthesis. The polyester-polyol is added with acetone into a three-neck ball-joint round bottom flask in a water bath. A reflux condenser, mechanical stirrer, digital thermometer, and nitrogen inlet are attached to the flask. The solution is heated to 40°C followed by the addition of short-chain diols and DBTDL catalyst. Once solids have dissolved, the diisocyanate is added dropwise. The temperature is increased to 55°C and the reaction progress is monitored at 20-min intervals using *N*-dibutylamine back titration of the isocyanate in solution. After the theoretical NCO content is reached, the reaction is cooled to 40°C, and the ionizing agent is added. After 10 min, EDA is added to the solution dropwise along with acetone to control the viscosity of the solution followed by dropwise addition of deionized water with continuous mechanical stirring for 1 h. The dispersion is heated to 35°C under vacuum and constant stirring for 30 min to remove the acetone. Individual PUD synthesis procedures are provided in the supporting information.

2.2.3 | General procedure for double-reactor synthesis method of water dispersed polymers

The double-reactor synthesis method is performed as described for the single-reactor synthesis up to the point of ionizing agent addition, after which the dispersion reactor is set up by adding deionized water into a reaction kettle in a water bath with a three-neck cover and a mechanical stirrer. A recipe amount of EDA is dissolved in the dispersion reactor at room temperature, and the pre-polymer is added slowly into the reactor. The pre-polymer reactor is rinsed with a minimal amount of acetone and stirring is continued for 1 h. Acetone removal is performed as for the single-reactor method.

2.2.4 | Polyurethane-urea film preparation

Films of PUDs were prepared by adding 20 g of the polyurethane dispersion in a round polytetrafluoroethylene mold and dried at room temperature for 48 h. The obtained films were dried in a vacuum oven at 70°C until the weight was constant.

2.3 | Characterization methods

2.3.1 | Dynamic light scattering analysis

Particle size and zeta potential of PUD were determined using Malvern Instruments Zetasizer Nano. Samples for dynamic light scattering were prepared by step dilution to 1:2000 concentration. Two samples of each PUD were analyzed at 25°C.

2.3.2 | Nuclear magnetic resonance analysis

^{1}H NMR and ^{13}C NMR spectra were recorded on a JOEL ECA 500 MHz NMR at ambient temperature. Samples were prepared by dissolving 90 mg of film in 1 mL of deuterated dimethyl sulfoxide.

2.3.3 | Thermal gravimetric analysis

Thermal gravimetric analysis (TGA) was carried out on TA Instrument Discovery SDT 650 simultaneous DSC/TGA from 30 to 650°C using temperature a ramp of 10°C/min in nitrogen atmosphere.

2.3.4 | Gel permeation chromatography analysis

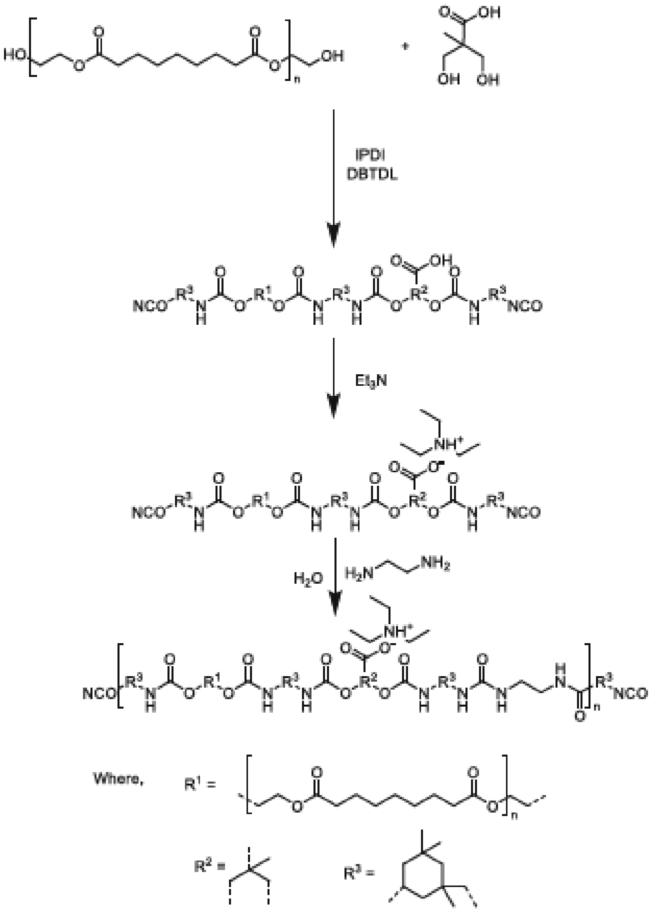
Gel permeation chromatography (GPC) was carried out using Shimada LC-2050 GPC with Wyatt Instrument MALS light scattering, OptiLab differential refractive index detectors. A polystyrene standard was used to calibrate molecular weight and molecular number. Dimethylformamide (DMF) was used as solvent and eluent at a concentration of 5 mg/mL at 40°C.

2.3.5 | Lamination testing

Laminate samples were prepared and tested per ASTM D1876. PUD was diluted to 20% solid content then an even 25-micrometer layer was applied using a knife spreader to a polyhydroxyalkanoate (PHA) sheet with an 80 mm unbonded area on one side of the sheet. After the water had evaporated a second PHA sheet was applied over the adhesive, and the sample was cured in an oven at 60°C for 15 min then at room temperature for an additional 4 days. The sheet was cut into 25 mm × 305 mm strips, where 229 mm is bonded by adhesive and 76 mm is left unbonded. The laminate samples were tested using UTM AGS-X 20KN by Shimadzu Corporation.

2.3.6 | Biodegradation, respirometry, and scanning electron microscopy analysis

Samples were buried in compost collected from a home composting bin from Roger's Garden at UC San Diego. For imaging analysis of biodegradation, composting samples were maintained at 45°C and 75%–85% relative humidity. The compost was mixed weekly. Respirometry was performed under aerobic conditions at 58°C according to ASTM D5338-15 (Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials under Controlled Composting Conditions, Incorporating Thermophilic Temperatures) using an Echo Respirometer equipped with CO_2, O_2, and humidity sensors (Echo Instruments, Slovenia). In preparation for scanning electron microscopy (SEM), samples were fixed and dehydrated as described in Gunawan et al.[19] Samples attached to carbon tape were coated with a thin layer of iridium using an Emitech K575X Sputter Coater, excess of which was dusted off with compressed air prior to imaging. All samples were imaged at high vacuum using an FEI Quanta FEG 250 scanning electron microscope at a voltage of 10.0 kV.



SCHEME 1 Reaction route for PUD 5 and 6.

3 | RESULTS AND DISCUSSION

3.1 | Bio-based polyurethane-urea dispersion synthesis

In total, seven biobased PUDs were synthesized, all of which followed the same general reaction scheme, as diagrammed for PUDs 5 and 6 in Scheme 1. To explore the adhesive ability of high biocontent PUDs, multiple diisocyanates, emulsifiers, polyester-polyols, and chain extenders were utilized, as detailed in Table 1.

PUD 5 is a single reactor setup where the final step involving chain extension using ethylenediamine occurs first followed by water dispersion. PUD 6 uses the double reactor method where ethylenediamine is dissolved in water and chain extension and dispersion occur simultaneously.

PUDs 1, 4, 6, and 7 were synthesized using the double-reactor methodology, while PUDs 2, 3, and 5 were synthesized using the single-reactor methodology. Both methodologies were equally successful in the formation of IPDI-based PUDs, but the single reactor method was unable to form stable TDI-based PUDs due to the higher reactivity of aromatic TDI. Additionally based on the T-peel test results, PUD 6 showed higher adhesion separation force than PUD 5 despite similar formulations. The single reactor methodology did require additional solvent to manage the pre-polymer viscosity prior to the addition of water, but there was no increased difficulty in solvent removal after the dispersion formed. The single reactor methodology allowed the synthesis of PUDs much more efficiently, as typically the dispersion reactor necessitates a doubling of all lab equipment.

While the bio-sourced content of TPUs has been reported in excess of 85%, PUDs have lagged behind due to the need for water-stabilizing agents.[27,28] Vegetable oil-based PUDs have reported biobased content up to 75%, but they contained monomers not currently used in industrial PUD production.[29] Fortunately, the PUDs prepared are synthesized from commercially available monomers and offer a drop-in replacement with current

TABLE 1 Composition and biobased-carbon content of PUD.

PUD	Polyol	M_w (Da)	Isocyanate	Emulsifier/ionizer	Chain extenders	Biobased content (%)
1	SuA/AzA/PDO	2200	IPDI	DMPA/TEA	PDO/EDA	71.3
2	SuA/3MPeDO	2300	IPDI	DMPA/TEA	EDA	70.0
3	SuA/AzA/PDO	2200	IPDI	MDEA/AcA	EDA	70.5
4	SuA/AzA/PDO	2200	TDI	DMPA/TEA	EDA	77.4
5	Emerox® 14550	2250	IPDI	DMPA/TEA	EDA	57.7
6	Emerox® 14550	2250	IPDI	DMPA/TEA	EDA	59.0
7	SuA/PDO	2600	IPDI	DMPA/TEA	EDA	74.5

TABLE 2 Average dispersion and adhesion properties of polyurethane-urea dispersions (Figures S1–S28).

PUD	DMPA/ MDEA content (%)	Particle size (nm)	Particle size Polydispersity	Zeta potential (mV)	Solid content (%)	T-Peel maximum force (gf/25 mm)
1	2.1	143.5	0.098	−47.6	28.1	1120.6
2	3.0	159.9	0.065	−39.8	28.6	840.4
3	2.7	145.9	0.293	+70.8	34.5	653.7
4	3.4	106.5	0.102	−35.5	20.1	933.8
5	3.0	221.2	0.313	−47.1	28.8	468.9
6	3.3	200.9	0.267	−51.5	31.8	1120.6
7	3.7	198.2	0.137	−45.1	32.4	1400.7

processes. The biocontent of the PUDs was determined by calculating the percentage of renewable carbon in each PUD. Biobased content in polymers ranged from 57.7% for PUD 5 up to 77.4% for PUD 4, whose high biobased content is due to the smaller molar mass of TDI relative to IPDI. Five of the seven synthesized samples displayed biobased content greater than 70%.

TABLE 3 GPC results of PUD films in DMF (Figures S43–S49).

PUD	M_w (g/Mol)	M_n (g/Mol)	PDI
1	56,090	42,580	1.317
2	68,690	31,300	2.195
3	124,200	85,700	1.449
4	86,920	62,310	1.395
5	82,890	42,890	1.933
6	96,300	37,000	2.603
7	84,310	51,410	1.640

3.2 | Properties of bio-based polyurethane-urea dispersions are comparable to petroleum-derived polyurethane-urea dispersions

As shown in Table 2, the average particle size in the PUDs ranged from 106.5 nm for PUD 4 to 221.2 nm for PUD 5. The particle size results of the PUDs can be attributed to the well-known effect of higher acid number resulting in smaller particle size.[30] This is seen in PUD 4 showing the smallest particle size while having the highest DMPA content of the 2200–2300 molecular weight polyol-based PUDs, while the particle size of PUD 7 is aided by the higher molecular weight of the polyol component. The high polydispersity of PUD 5 and 6 is likely due to modifiers added to the polyol by the manufacturer, as multiple peaks appear in the DLS data. Multiple particle sizes also appear in PUD 3, indicating partial agglomeration of unionized segments. Zeta potential analysis indicates moderate to strong colloidal stability of the PUDs.[31] PUDs 1, 2, 4–7 range between −35.5 and −51.5 mV due to the anionic charge present in the DMPA. PUD 3 shows excellent colloidal stability at +70.8 mV caused by the cationic charge present in MDEA. Solid content of the IPDI-based PUDs varied between 28.1% and 34.5% while the TDI-based PUD had a solid content of 20.1% as additional water was necessary to successfully disperse the prepolymer. The solid content of the IPDI-based PUDs matches closely to what is found in commercially available petroleum-based non-biodegradable PUDs for 28%–32% solids.[32]

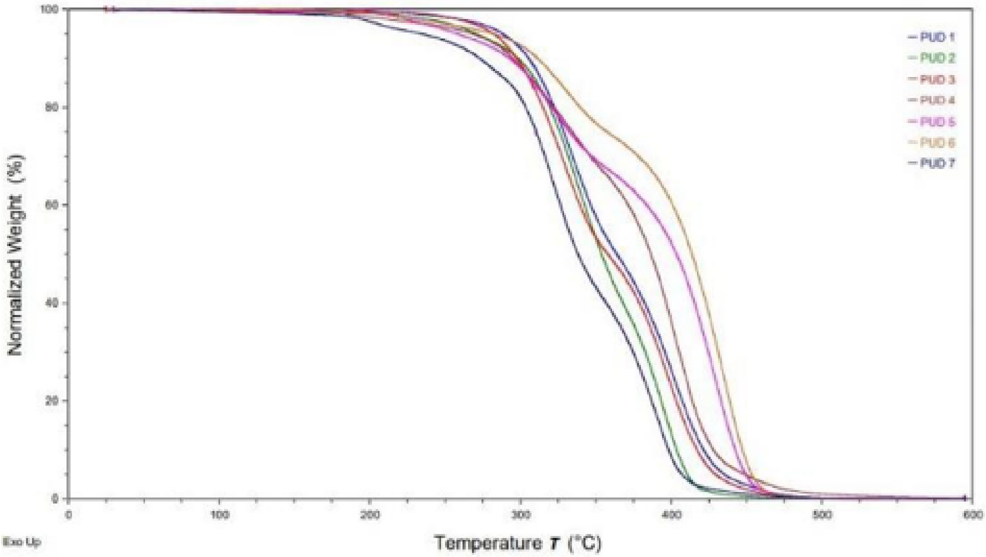


FIGURE 1 Combined thermogravimetric analysis graph of polyurethane-urea dispersion films. [Color figure can be viewed at wileyonlinelibrary.com]

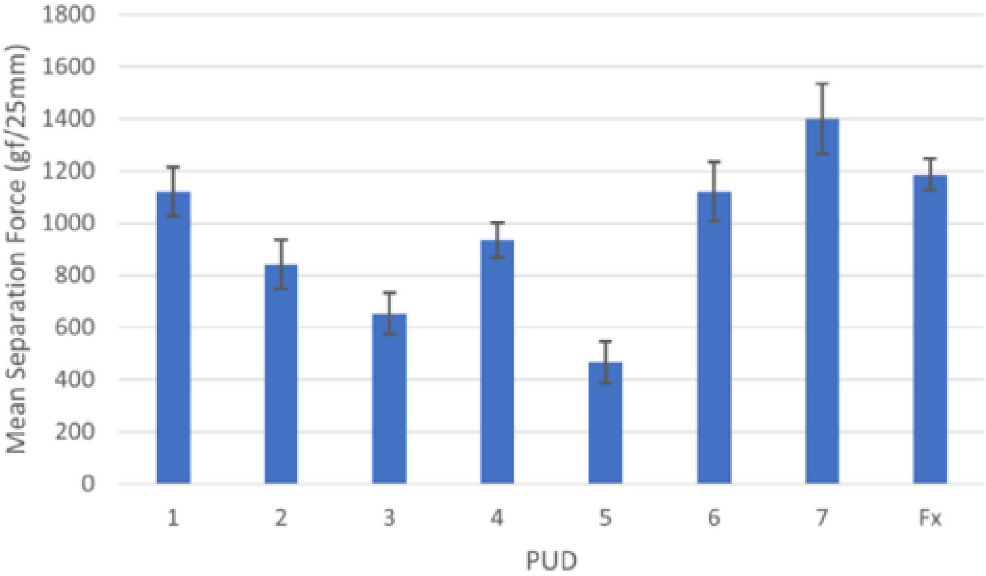


FIGURE 2 Maximum adhesive separation force average and error bars indicating 2σ variance of T-Peel test across 6 trials of each PUD sample and 4 trials of non-biodegradable commercial adhesive. [Color figure can be viewed at wileyonlinelibrary.com]

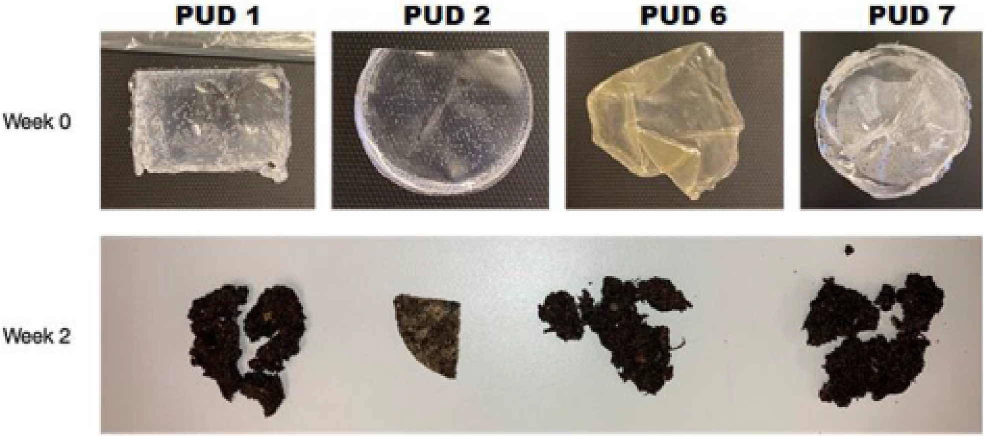


FIGURE 3 Degradation of films in home compost conditions. [Color figure can be viewed at wileyonlinelibrary.com]

3.3 | Properties of bio-based polyurethane-urea films are comparable to petroleum-based polyurethane-urea films

PUD films were analyzed using TGA, GPC, and nuclear magnetic resonance (NMR). GPC data shown in Table 3 indicates successful polymer formation, as the molecular weight of all samples ranges between 55 and 124 kDa. None of the film samples' carbon NMR traces show peaks in the 120–125 ppm range where the isocyanate carbon is found for IPDI and TDI, and the addition of peaks in the 150–160 ppm range indicates the formation of polyurethane and polyurea bonds in all PUD films (Figures S29–S42). TGA data shown in Figure 1 shows strong thermal stability of all films below 200°C. Hydrogen bonding caused by the urethane and urea linkages in the structure result in hard segments with a crystalline structure, separated by long polyester chains with non-crystalline soft segments. This hybrid semi-crystalline and linear structure results in strong adhesion when the PUD is heated and cured onto the substrate.

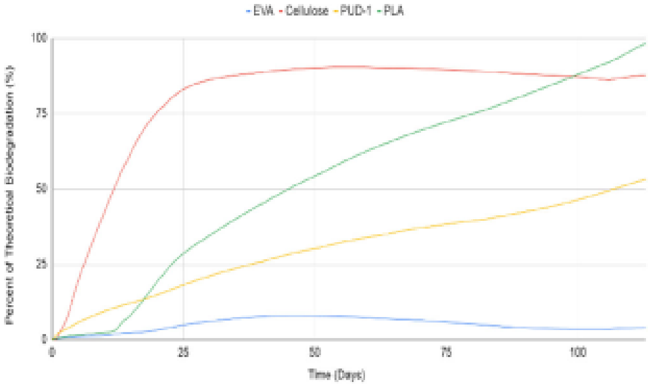


FIGURE 4 Biodegradation of PUD 1 film through respirometer analysis. [Color figure can be viewed at wileyonlinelibrary.com]

3.4 | Adhesion properties of bio-based polyurethane-urea laminates are comparable to petroleum-based polyurethane-urea films

Strong adhesion to the substrates is a result of the semi-crystalline structure of PUs. The cohesiveness of the adhesive is a result of the hydrogen bonding between hard segments between polymer chains, and the non-crystalline structure of the soft segment polyester allows melting and curing of the PU onto the substrate after removal of water. The laminate samples tested all showed fair to strong adhesion strength (Figure 2). Adhesion strength showed no correlation based on polyol, isocyanate, or hard-segment variance, but based on the peel strength doubling for PUD 5 and 6 significant difference is shown through single-reactor and double-reactor setups. The highest adhesion strength is shown in PUD 7, which has a higher M_w of its polyol component that in turn results in a higher soft-segment portion in the polymer. It can be inferred that the increase in soft-segment content caused an increase in the adhesion strength of the polymer.

3.5 | Bio-based polyurethane-urea films biodegrade in compost

PUD films for samples 1, 2, 6, and 7 were placed into compost and incubated under home composting conditions. PUDs 1, 6, and 7 were prioritized for biodegradation studies due to space limitations in the controlled composting system and their strong lamination testing. After 2 weeks, most of the films showed significant deterioration and adhesion to the compost, as shown in Figure 3. In contrast to the other PUDs, PUD 2 showed less adhesion to the compost and was structurally intact, though discoloration and scarring were apparent. The films were removed after 12 weeks, and visual inspection

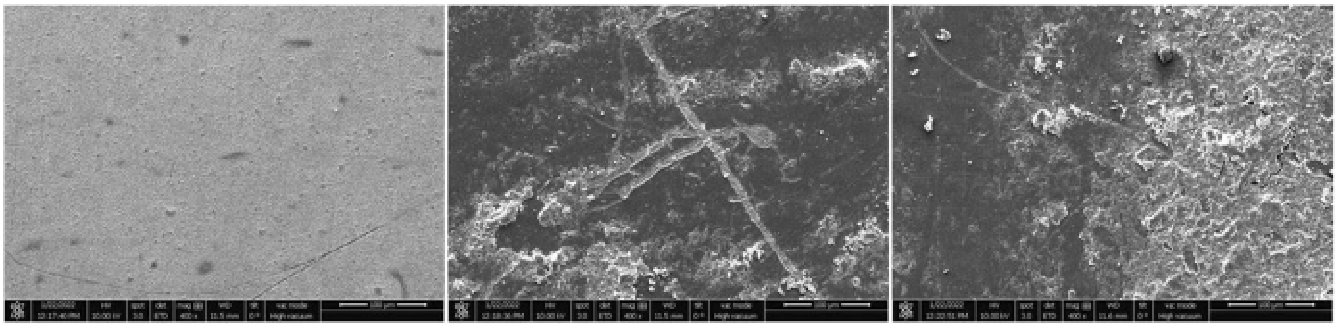


FIGURE 5 Scanning electron microscopy images are shown of PHA laminated adhesive samples containing non-biodegradable commercial adhesive (left), PUD 1 (center), and PUD 2 (right), after 4 weeks in home compost conditions.

showed that all films had broken into several fragments. The resulting samples were clumped with the compost and unable to be analyzed via GPC. Biodegradation of PUD 1 under industrial aerobic composting conditions was also determined quantitatively according to ASTM D5338 respirometry standards. After approximately 113 days, PUD 1 showed 53.51% biodegradation, in contrast to only 3.99% as detected for a non-biodegradable material (EVA) and 98.8% for polylactic acid (PLA), which is known to biodegrade under industrial compost conditions (Figure 4). The slower rate of degradation of the film may be due to the fact that mechanical shredding of the film was not possible due to its tackiness. Thus, the PUD film was cut into larger pieces than the shredded PLA, and the powdered cellulose was used as a positive control in this experiment.

3.6 | Bio-based polyurethane-urea laminates biodegrade in compost

Laminated samples of PUD 1, PUD 2, and a non-biodegradable control sample were incubated under home compost conditions and removed after 4 weeks for SEM imaging, as shown in Figure 5. The control sample shows no signs of degradation, but both PUD laminates show significant scarring and signs of degradation after 4 weeks. When mechanical testing was attempted to determine T-peel strength, the control sample had a substrate failure and no adhesive separation occurred. PUD laminates separated with less than 100 gf/25 mm.

FIGURE 6 Polyhydroxyalkanoate-based clear sheet laminated with PUD 1 before compost (top) and after 2 weeks in compost (bottom). [Color figure can be viewed at wileyonlinelibrary.com]

Figure 6 shows the biodegradation progress of the laminated PHA-based films with PUD 1 before and after 2 weeks in home compost. After 4 weeks, the laminated PHA film had fully degraded into the compost, and recovery was not possible. The experiment was repeated using laminated printed PHA films with PUD 1 in home compost conditions. The biodegradation of the laminated films is shown in Figure 7 over the course of 3 months. After 4 months mark the films had degraded and recovery was not possible.

PUD films and laminates compared favorably with other biodegradable PUs. The lower molecular weight in comparison to TPUs and foams allows rapid biodegradation as shown in the imaging. In TPU biodegradation samples have been isolated after 9 weeks and GPC analysis showed a decrease in M_w values of 33 to 57%, whereas for the PUDs synthesized it was no longer possible to find the remains of the PUD samples after 4 weeks in compost.[26]

4 | CONCLUSION

Several highly biobased, biodegradable, and environmentally friendly polyurethane dispersions for adhesive application were synthesized utilizing multiple isocyanates, polyester-polyols, and chain extenders. Different synthesis methods and anionic and cationic dispersions were examined. The dispersions showed good stability based on DLS data. The GPC analysis showed polymerization formation in the 80–90 kDa range. The PHA laminates produced using the PUDs as adhesive showed good adhesion strength between 600 and 1400 gf/25 mm. Lastly, the biodegradability of both PUD films and PUD laminated samples was demonstrated. Based on visual

FIGURE 7 Progression of biodegradation of printed polyhydroxyalkanoate-based lamination with PUD 1 over the course of 3 months. [Color figure can be viewed at wileyonlinelibrary.com]

inspection the films began biodegrading in home compost within the first 2 weeks, and after 12 weeks had broken down into several fragments resulting in compost clumped together by the adhesive. The PHA films laminated using the PUDs were also shown to biodegrade through mechanical testing and SEM imaging. The laminated films showed little adhesion ability after composting, and SEM imaging showed degradation of the laminate samples.

Based on these findings, the PUDs developed show great potential for use in short-life adhesive applications. The adhesion strength is comparable to non-biodegradable petroleum-based products available. The use of commercially available, renewable precursors allows for the preparation of these PUDs similar to those currently manufactured. Further, the low viscosity of these PUDs also allows drop-in use in a variety of adhesive applications, including single-use plastic composites, food packaging, plastic labels, and so forth. Excellent adhesive properties along with rapid degradation of the composite materials tested indicate the PUDs would be strong candidates for replacement of non-biodegradable adhesives in existing composite materials, allowing compost biodegradation of some products currently destined to end up in landfills at their end of useful life.

AUTHOR CONTRIBUTIONS

Amal Patel: Formal analysis (lead); methodology (lead); writing – original draft (lead). **Bhausaheb Rajput**: Methodology (supporting); supervision (supporting); writing – review and editing (supporting). **Thien An Phung Hai:** Investigation (supporting); methodology (supporting). **Daniel Zhen:** Formal analysis (equal); investigation (equal); writing – original draft (supporting). **Natasha Gunawan:** Data curation (supporting). **Marissa Tessman:** Investigation (supporting). **Jaysen Reindel:** Data curation (supporting). **Ryan Simkovsky:** Investigation (supporting); supervision (supporting); writing – review and editing (supporting). **Robert Pomeroy**: Supervision (supporting). **Naser Pourahmady**: Supervision (equal). **Stephen Mayfield:** Supervision (supporting). **Jenna Shepherd:** Data curation (supporting). **Michael D. Burkart:** Conceptualization (lead); funding acquisition (lead); project administration (lead); supervision (lead); writing – review and editing (supporting).

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CONFLICT OF INTEREST STATEMENT

The authors declare the following financial interests/personal relationships, which may be considered as potential competing interests: Michael D. Burkart, Robert S. Pomeroy, and Stephen P. Mayfield are founders of, and hold an equity position in, Algenesis Inc. Natasha R. Gunawan, Marissa Tessman, Daniel Zhen, and Ryan Simkovsky, are employees and shareholders in Algenesis Inc., a company that could benefit from this research.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supplementary material of this article.

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