A Green Approach Toward Oleic- and Undecylenic Acid-Derived Polyurethanes

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ABSTRACT: Naturally occurring oleic and undecylenic acids were used as raw materials for the synthesis of novel polyurethanes (PUs). The application of environmentally friendly thiol-ene additions to 10-undecenoate and oleate derivatives was studied with the goal of obtaining renewable diols. The resulting monomers were then polymerized with 4,4′-methylenebis (phenylisocyanate), in *N*,*N*-dimethylformamide solution using tin (II) 2-ethylhexanoate as catalyst, to produce the corresponding thermoplastic PUs (TPUs). Also, ultrasound irradiation has been tested to improve the synthesis of PU. Under these conditions, TPUs were obtained in high yields (80–99%) with weight-average molecular weights in the 36–83 kDa range. The chemical structures of PUs were assessed by FTIR and NMR spectroscopy. The thermal and mechanical properties of the synthesized TPUs have been studied and they showed a clear dependence on the structure of the parent diol. MTT test was carried out to asses the potential cytotoxicity of the prepared PUs, indicating no cytotoxic response. © 2011 Wiley Periodicals, Inc. J Polym Sci Part A: Polym Chem 49: 2407–2416, 2011

KEYWORDS: oleic acid; polyurethanes; renewable resources; thermoplastics; thiol-ene; undecylenic acid

INTRODUCTION To date, a wide range of industrial materials such as solvents, fuels, synthetic fibers, and chemical products are being manufactured from petroleum resources. However, rapid depletion of fossil and petroleum resources is encouraging current and future chemists to orient their research toward designing safer chemicals, products, and processes from renewable feedstock with an increased awareness of environmental and industrial impact.[1]

Nature offers an abundance of opportunities for designing novel monomers and shaping structural and functional polymers in its wide variety of raw materials.[2] Presently, their relative use for synthesis of monomers and polymers compared to petrochemicals is small. Natural oils, such as vegetable oils provide interesting feedstock—triglyceride fatty acids—that beyond their use in food allow additional chemistry that yields either opportunities for replacing petrochemicals or may be directly used to synthesize bioinspired materials.[3–6] Fatty acids have been used in various classes of biodegradable polymers but have been largely confined to polyanhydrides, polyesters, and poly(ester-anhydrides). In these polymers, fatty acid monomers obtained from natural sources were incorporated in the polymer backbone to obtain the desired properties.[7]

Vegetable oils are becoming extremely important as renewable resources for the preparation of polyols required for the polyurethane (PU) industry.[8] Polyols from natural oils, such as soybean, castor, and palm oils are increasingly being viewed by industry as a viable alternative to hydrocarbon-based feedstocks. In sustainable materials, PUs are currently prepared starting from renewable polyols, while the second partner, isocyanate, is mainly made from petroleum resources.[9,10] There is limited literature available concerning the synthesis of isocyanate compounds based on plant oils. Küsefoglu and Çayli[11] reported the functionalization of soybean oil with isocyanate moieties, and demonstrated that these plant-based isocyanates are suitable for PU preparation. On the other hand, recently Narine and co-workers[12] have developed methodologies for the synthesis of isocyanates and polyols from vegetable oils and corresponding biobased PUs entirely from lipid feedstock. Moreover, concerning nonisocyanate methods for the preparation of PUs derived from plat oils, two methodologies have been described: the reaction of cyclic carbonates with amines[13] and the more recent self-condensation approach of AB-type monomers.[14]

Classically, the reaction between a thiol and a double bond has received significant attention as candidate for many applications including coatings, adhesives, dental materials, and imprinting lithography. Resurgence over the past decades has occurred in response to the benefits thiol-ene coupling presents for polymer synthesis: tolerance to many different reaction conditions/solvents, clearly defined reaction pathways/products, and facile synthetic strategies from a range of easily obtained starting materials.[15] Thus, thiol-ene chemistry has recently emerged as a powerful tool for

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synthetic chemistry and polymer functionalization that has the potential to fall within the realm of click chemistry.[16–18] The thiol-ene coupling makes use of the high nucleophilicity of the sulfhydryl moiety and proceeds under physiological conditions. The formed thioether linkage is very stable under physiological conditions and resists a strong basic or acidic environment and is also stable toward reducing agents; however, it is susceptible toward oxidizing agents. The robust nature of thiol-ene chemistry allows for the preparation of well-defined materials with few structural limitations and synthetic requirements.[19] While both heat and light have been used to generate radicals that initiate the thiol-ene radical chain process, the use of light has enormous advantages for small molecule synthesis, surface and polymer modification, and polymerization reactions. A vast array of work has been performed in an effort to understand and implement radical-mediated thiol-ene reactions, primarily focusing on the photoinitiated reactions. This large body of literature is detailed in very recent review articles.[20–23]

In the last decade, many authors have reported the use of vegetable oils as feedstock for UV-curable systems,[24–26] and although UV-curable chemistries based on thiol-ene functionality offer many advantages,[27,28] only recently thiol-ene UV-curable coatings using vegetable oils is reported.[29]

In particular, thiol-ene click chemistry of fatty acid derivatives,[30,31] obtained from plant oils, is a promising route that can be used for the synthesis of novel chemical intermediates from renewable resources. Our research applies the thiol-ene click chemistry of unsaturated fatty acid ester derivatives with hydroxyl-functionalized thiols for its ability to add hydroxyl functionality in lieu of double bounds. This methodology provides a green approach toward novel plant-derived diols.[32]

In this work, we report UV light-mediated synthesis of four diols from oleic acid and 10-undecenoic acid derivatives. Oleic and 10-undecenoic acids are the major products of high oleic sunflower oil saponification and castor oil pyrolysis,[33] respectively. We will focus our discussion on the synthesis of monomer diols which have been used in the synthesis of PUs as well as characterization and properties of the resulting PUs.

EXPERIMENTAL

Materials

Methyl oleate (OLM) and methyl 10-undecenoate (UDM) were synthesized from oleic acid (90% Mallinckrodt, St. Louis, MO) and 10-undecenoic acid (98%, Aldrich, Steinheim, Germany) following standard methods. Allyl 10-undecenoate (UDA) was synthesized following a previously reported procedure.[32] The following chemicals were purchased from Aldrich (Steinheim, Germany) and used as received: lithium aluminum hydride, $LiAlH_4$ (95%), acetonitrile, allyl alcohol (>98%), 2,2-dimethoxy-2-phenylacetophenone (DMPA; 99%), 2-mercaptoethanol (99%), tin (II) 2-ethylhexanoate, and 4,4′-methylenebis(phenylisocyanate) (MDI). Tetrahydrofuran (THF) was distilled from sodium immediately before use; *N*,*N*-dimethylformamide (DMF) was dried with CaH_2 for 24 h and freshly distilled before use. Phosphate-buffered solution (PBS) of pH 7.4 from Sigma (Steinheim, Germany) was used as received. Thermanox (TMX) control disks were supplied by Labclinics S.L. (Barcelona, Spain), and aqueous solutions of Triton X-100 were supplied by Aldrich (Steinheim, Germany). Tissue culture media, additives, and 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) were purchased from Sigma (Steinheim, Germany). The fetal bovine serum was obtained from Gibco (Paisley, UK), and L-glutamine, penicillin, and streptomycin were from Sigma (Steinheim, Germany).

Synthesis of Allyl Oleate (OLA)

To a 250-mL round-bottom flask, 26 g (0.092 mol) of oleic acid, an excess of allyl alcohol 25 mL (0.37 mol), and *p*-toluensulphonic acid as a catalyst were added, and the mixture was refluxed and magnetically stirred for 8 h. Once the reaction was completed, the mixture was washed with ethyl ether and 10% sodium bicarbonate solution, dried over anhydrous magnesium sulphate and filtered. The solvent was evaporated off under reduced pressure. The product was purified by column chromatography using hexane:ethyl acetate, 8:2, as eluent, to afford pure allyl oleate (OLA) as viscous oil, in a 80% yield.

^{1}H NMR [$CDCl_3$, tetramethylsilane (TMS), δ (ppm)]: 5.88 (m, —CH=C), 5.35 (m, —HC=CH—, 2H), 5.25 (m, C=CH_2), 4.58 (d, —OCH_2), 2.37 (t, —CH_2—CO—), 2.01 (m, —CH_2—CH=CH—, 4H), 1.62 (t, —CH_2—CH_2—COO—), 1.38–1.22 (m, —CH_2—, 20 H), 0.93 (CH_3—). ^{13}C NMR [$CDCl_3$, TMS, δ (ppm)]: 173.80 (s), 132.15 (d), 130.00 (d), 129.80 (d), 118.02 (t), 64.73 (t), 34.10 (t), 32.15 (t), 32.1 (t), 29.81 (t), 29.62 (t), 29.55 (t), 29.25 (t), 29.21 (t), 29.12 (t), 29.00 (t), 27.21 (t), 27.15 (t), 24.5 (t), 22.32 (t), 14.1 (q).

Synthesis of 3-(2-Hydroxyethylthio)propyl 11-(2-hydroxyethylthio) Undecanoate (UDA-diol): Thiol-Ene Coupling of UDA with 2-Mercaptoethanol

In a 25-mL flask, 5.0 g (22 mmol) of UDA reacted with 4.3 g (55 mmol) of mercaptoethanol. The radical initiator, DMPA, was added in the proportion of 0.3% mol init./mol C=C. The amount of acetonitrile necessary to dissolve the photoinitiator was added. The reaction was carried out at room temperature, without deoxygenation, by irradiation with two 9 W UV lamps (λ = 365 nm). After few minutes, a white solid was precipitated. The completion of the reaction was confirmed by ^{1}H NMR by the complete disappearance of the double bond signals that appear in the region of 5–6 ppm. The mixture was crystallized from ether, filtered, washed with cold ether and hexane, and dried under vacuum (yield 98%).

^{1}H NMR [$CDCl_3$, TMS, δ, ppm)]: 4.15 (t, —OCH_2), 3.73 (t, —CH_2—OH), 3.70 (t, —CH_2—OH), 2.73 (t, $HOCH_2$—CH_2—S—), 2.72 (t, $HOCH_2$—CH_2—S—), 2.59 (t, —O—$(CH_2)_2$—CH_2—S—), 2.51 (—CH_2—CH_2—S), 2.29 (CH_2—COO—), 1.93 (m, —CH_2—), 1.59 (m, —CH_2—, 4H), 1.38–1.26 (m, —CH_2—, 12 H). ^{13}C NMR [$CDCl_3$, TMS, δ (ppm)]: 173.96 (s), 62.79 (t), 60.40 (t), 60.28 (t), 35.43 (t), 35.40 (t), 34.40 (t), 31.73 (t), 29.84 (t), 29.51 (t), 29.45 (t), 29.32 (t), 29.26 (t), 29.22 (t), 28.94 (t), 28.91 (t), 28.23 (t), 25.06 (t).

Synthesis of 3-(2-Hydroxyethylthio)propyl 9- and 10-(2-hydroxyethylthio) Octadecanoate as a Mixture of Isomers (OLA-diol): Thiol-Ene Coupling of OLA with 2-Mercaptoethanol

OLA-diol was synthesized following the procedure described for UDA-diol but higher ratio of radical initiator was used (1.7% mol init./mol C=C). The product was purified by column chromatography using hexane:ethyl acetate, 1:1, as eluent, to afford OLA-diol as viscous oil, in a 80% yield.

^{1}H NMR [$CDCl_3$, TMS, δ (ppm)]: 4.10 (t, —COO—CH_2), 3.66 (q, $HOCH_2$—), 3.63 (q, $HOCH_2$—), 2.67 (t, $HOCH_2$—CH_2—S—), 2.65 (t, $HOCH_2$—CH_2—S—), 2.53 (t, —O—$(CH_2)_2$—CH_2—S—), 2.50 (m, —CH—S—), 2.23 (t, —CH_2—COO—), 1.85 (m, —O—CH_2—CH_2—CH_2—S) 1.56–1.25 (m, —CH_2—, 28H), 0.81 (t, CH_3). ^{13}C NMR [$CDCl_3$, TMS, δ (ppm)]: 174 (s), 62.55 (t), 60.50 (t), 60.25 (t), 45.80 (d), 35.04 (t), 34.99 (t), 34.98 (t), 34.10 (t), 33.75 (t), 31.72 (t), 29.68 (t), 29.64 (t), 29.61 (t), 29.52 (t), 29.42 (t), 29.31 (t), 29.22 (t), 29.15 (t), 28.80 (t), 28.01 (t), 26.60 (t), 25.00 (t), 22.65 (t), 14.11 (q).

Synthesis of Methyl 11-(2-Hydroxyethylthio)undecanoate (UDM-OH): Thiol-Ene Coupling of UDM with 2-Mercaptoethanol

UDM-OH was synthesized following the procedure described for UDA-diol but in this case no radical initiator was used. The product was obtained as a white solid with 95% yield.

^{1}H NMR [$CDCl_3$, TMS, δ (ppm)]: 3.73 (t, HO—CH_2—CH_2—S—), 3.66 (s, —OCH_3), 2.73 (t, $HOCH_2$—CH_2—S—), 2.51 (t, —S—CH_2), 2.30 (t, —CH_2—COO), 1.63–1.27 (m, —CH_2—, 16H). ^{13}C NMR [$CDCl_3$, TMS, δ (ppm)]: 174.51 (s), 60.44 (t), 51.59 (q), 35.36 (t), 34.22 (t), 31.80 (t), 29.86 (t), 29.52 (t), 29.45 (t), 29.32 (t), 29.28 (t), 29.23 (t), 28.93 (t), 25.05 (t).

Synthesis of Methyl 9- and 10-(2-Hydroxyethylthio)octadecanoate as a Mixture of Isomers (OLM-OH): Thiol-Ene Coupling of OLM with 2-Mercaptoethanol

OLM-OH was synthesized following the procedure described for UDA-diol but higher ratio of radical initiator was used (1.7% mol init./mol C=C). The product was obtained as viscous oil with 80% yield.

^{1}H NMR [$CDCl_3$, TMS, δ (ppm)]: 3.69 (t, $HOCH_2$—CH_2—S—), 3.66 (s, —OCH_3), 2.71 (t, $HOCH_2$—CH_2—S—), 2.57 (m, —CH—S—), 2.29 (t, —CH_2—COO), 1.63–1.25 (m, —CH_2—, 28H), 0.87 (t, CH_3). ^{13}C NMR [$CDCl_3$, TMS, δ (ppm)]: 174.53 (s), 60.89 (t), 51.64 (q), 45.95 (d), 35.14 (t), 34.27 (t), 33.95 (t), 32.03 (t), 29.83 (t), 29.75 (t), 29.68 (t), 29.62 (t), 29.54 (t), 29.48 (t), 29.42 (t), 29.35 (t), 29.22 (t), 26.95 (t), 25.05 (t), 22.83 (t), 14.28 (q).

Synthesis of 11-(2-Hydroxyethylthio)undecan-1-ol (UDM-diol)

A 250-mL, two-necked, round-bottom flask equipped with a Teflon-coated magnetic bar and a pressure-equalized dropping funnel was charged with $LiAlH_4$ (0.42 g, 0.011 mol) and anhydrous THF (15 mL) under argon. UDM-OH (3 g, 0.011 mol) dissolved in 15 mL of anhydrous THF was added slowly with stirring for 1 h. Anhydrous THF (3 $\times$ 10 mL) was added as the viscosity increased. After 30 min, excess $LiAlH_4$ was decomposed by the addition of 20 mL of ethyl acetate dropwise, then a saturated 10% H_2SO_4 aqueous solution (60 mL) was added, the phases were separated, and the aqueous layer was extracted with ethyl acetate. The combined organic phase was washed with a saturated aqueous NaCl solution, dried over anhydrous magnesium sulfate, filtered, and the solvent was removed under reduced pressure. The solid product was recrystallized from heptane to obtain a white solid (yield 80%).

^{1}H NMR [$CDCl_3$, TMS, δ (ppm)]: 3.71 (t, $HOCH_2$—CH_2—S—), 3.64 (t, $HOCH_2$—), 2.73 (t, $HOCH_2$—CH_2—S—), 2.51 (t, —S—CH_2—), 1.58 (m, —CH_2—CH_2OH), 1.5 (m, —CH_2—CH_2—S—), 1.37–1.25 (m, —CH_2—, 14H). ^{13}C NMR [$CDCl_3$, TMS, δ (ppm)]: 63.30 (t), 60.30 (t), 35.55 (t), 33.00 (t), 31.80 (t), 29.93 (t), 29.74 (t), 29.67 (t), 29.65 (t), 29.59 (t) 29.38(t), 29.02 (t), 25.93 (t).

Synthesis of 9- and 10-(2-Hydroxyethylthio) octadecan-1-ol (OLM-diol)

OLM-diol was synthesized following the procedure described for UDM-diol. The product was dissolved in ethyl ether (5 mL) and crystallized (−20 °C) with 75 % yield.

^{1}H NMR [$CDCl_3$, TMS, δ (ppm)]: 3.69 (t, $HOCH_2$—CH_2—S—), 3.66 (t, $HOCH_2$—), 2.72 (t, $HOCH_2$—CH_2—S—), 2.58 (m, —CH—S—), 1.58–1.25 (m, —CH_2—, 30H), 0.88 (t, —CH_3). ^{13}C NMR [$CDCl_3$,TMS, δ (ppm)]: 63.00 (t), 60.67 (t), 45.80 (d), 34.99 (t), 34.90 (t), 33.80 (t), 32.72 (t), 31.86 (t), 29.68 (t), 29.57 (t), 29.48 (t), 29.44 (t), 29.35 (t), 29.28 (t), 26.77 (t), 26.71 (t), 26.69 (t), 25.73 (t), 22.65 (t), 14.11 (q).

General Procedure for Polyurethanes Synthesis

A dry 50 mL round-bottom flask was charged with 12 mL of DMF, 6 mmol of diol (UDM-diol, OLM-diol, UDA-diol, or OLA-diol), 6 mmol of MDI, and 2%, w/w (with respect to MDI) of tin (II) 2-ethylhexanoate. The flask was immersed into a 50 °C preheated silicone oil bath with magnetic stirring. The reaction was continued for 24 h, and the PUs were isolated as white solids by precipitation into diethyl ether. Purification of PUs was carried out by dissolving the polymer in the minimum volume of chloroform or THF and reprecipitation into diethyl ether. The pure polymers were dried under vacuum and stored in a desiccator until needed. Films were solution cast from DMF and dried at 50 °C for 1 day and then in a vacuum oven until constant weight.

Instrumentation

The FTIR spectra were recorded on a JASCO 680 FTIR spectrophotometer with a resolution of 2 cm^{-1} in the absorbance mode. An attenuated total reflection (ATR) accessory with thermal control and a diamond crystal (Golden Gate heated single-reflection diamond ATR, Specac. Teknokroma) was used to determine FTIR spectra. ^{1}H (400 MHz), ^{13}C (100.5 MHz) NMR spectra were obtained using a Varian Gemini 400 spectrometer with Fourier transform, $CDCl_3$ as solvent, and TMS as internal standard.

Calorimetric studies were carried out on a Mettler DSC821e and DSC822e thermal analyzer using N_2 as a purge gas (20 mL/min) at scanning rate of 10 °C/min. Thermal stability studies were carried out on a Mettler TGA/SDTA851e/LF/1100 with N_2 as a purge gas. The heating rate in the TGA dynamic mode was 10 °C/min. Isothermal measurements were carried out at 240, 250, and 260 °C. Degradation kinetics of polymers was studied using TGA with experimental data being processed using the Flynn method, which includes three isothermal and one dynamic TGA curves.[34] This method provides the activation energy dependence with temperature.

Mechanical properties were measured using a dynamic mechanical thermal analysis apparatus (TA DMA 2928) in the controlled force-tension film mode. The tensile assays were performed on rectangular films ($5 \times 3 \times 0.2$ mm^3) measuring the strain while applying a ramp of 3 N/min at 35 °C. A preload force of 0.01 N and a soak time of 5 min were used.

Sonication Techniques

The main sources of ultrasound used were a Branson 2510 horn system, operating at 42 KHz and used in the usual configuration whereby the horn was immersed to a depth of about 1.5 cm in the reaction mixture. Thermostatting around ambient temperature was achieved to ±1 °C by water bath surrounding the reaction vessel.

Hydrolytic Degradation Assays

Films of aliphatic PUs with a thickness of approximately 200 μm were prepared by casting at room temperature from a solution in THF. The films were cut into 10 mm diameter, 20–30 mg weight disks, which were dried under vacuum at 50 °C to constant weight. For incubation, samples were immersed in vials containing 10 mL of the sodium phosphate buffer (pH 7.4), and experiments were carried out at temperature of 60 °C. After incubation for the scheduled period of time, samples were removed, rinsed thoroughly with water, and dried to constant weight. Sample weighing and gel permeation chromatography (GPC) measurements were used to follow the evolution of the hydrodegradation.

Biocompatibility of Polymers

The negative control used was tissue culture plastic, TMX, and the positive control (toxic agent) was a 0.5% aqueous solution of Triton X-100. Disks of 10 mm diameter and 1 mm thickness of the polymers and the controls were used for direct and indirect biocompatibility experiments. The polymers were tested for cytotoxicity assay. All specimens were sterilized with ethylene oxide. The cells used in the primary cell culture were human fibroblasts and were cultured at 37 °C. The culture medium was Dubelcco's modified eagle medium (DMEM), rich in glucose, modified with 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid (HEPES) (Sigma, Steinheim, Germany) and supplemented with 10% fetal bovine serum, 200 mM L-glutamine, 100 units/mL penicillin, and 100 μg/mL streptomycin. The culture medium was changed at selected time intervals with care to cause little disturbance to culture conditions.

MTT Assay for Polymers

TMX, Triton, and disks of copolymers were set up in 5 mL of DMEM, fetal calf serum (FCS)-free medium. They were placed on a roller mixer at 37 °C, and the medium was removed at different time periods (1, 2, and 7 days) and replaced with another 5 mL of fresh medium. All the extracts were obtained under sterile conditions. Human fibroblasts were seeded at a density of 11×10^4 cells/mL in complete medium in a sterile 96-well culture plate and incubated to confluency. Then, the medium was replaced with the corresponding eluted extract and incubated at 37 °C in a humidified air with 5% CO_2 for 24 h. A solution of MTT was prepared in warm PBS and filtered before use. MTT, 10 μL, was added to all wells to give a final concentration of 0.5 mg/mL, and the plates were incubated at 37 °C, 5% CO_2 for 4 h. Excess medium and MTT were removed, and 100 μL of DMSO was added to all wells to dissolve the MTT taken up by the cells. This was mixed for 10 min, and the absorbance was measured with a Biotek ELX808 IU plate reader, using a test wavelength of 570 nm and a reference wavelength of 630 nm. The cell viability was calculated from equation 1:

$$\text{Relative cell viability} = 100 \times (OD_S - OD_B)/OD_C \quad (1)$$

where OD_S, OD_B, and OD_C are the optical densities of formazan production for the sample, blank (DMEM without cells), and control (Tween solution in free serum-supplemented DMEM), respectively. Results were normalized with respect to a negative control (TMX = 100%) and statistically tested with ANOVA ($p < 0.05$).

RESULTS AND DISCUSSION

Synthesis of Allyl 10-Undecenoate and Allyl Oleate

The synthesis of allyl ester of 10-undecenoic acid (UDA) was carried out by refluxing UDA, which is the major product of castor oil pyrolysis,[33] with an excess of allyl alcohol and using 2% *p*-toluenesulfonic acid as catalyst, for 6–8 h (Scheme 1).

The synthesis of OLA was carried out in a similar way as compared to than UDA but using oleic acid as fatty acid. The ^{1}H NMR spectrum of the product confirmed the expected structure, showing together with the five allyl protons a multiplet at 5.35 ppm corresponding to the two olefinic protons of the central double bond.

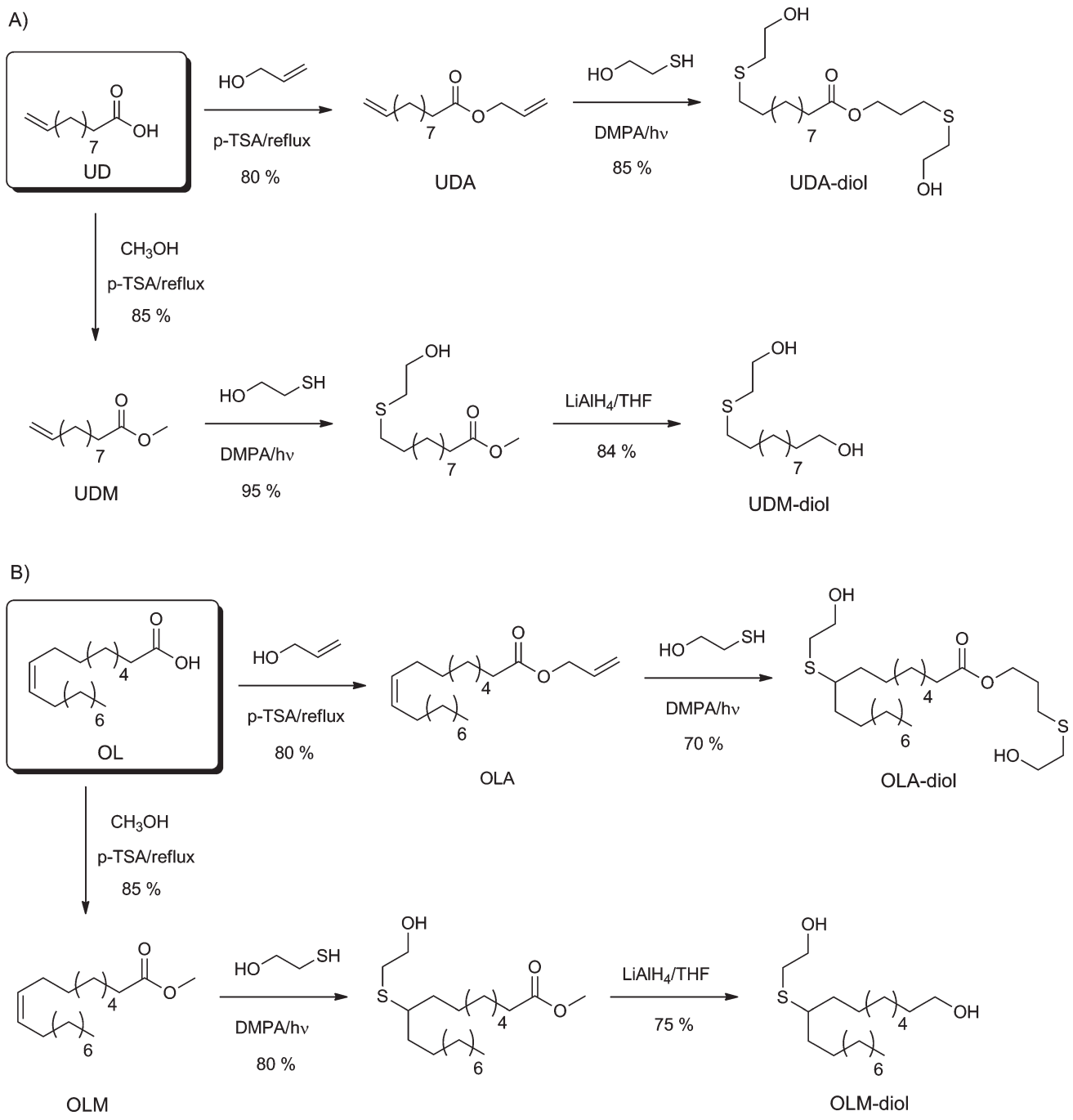
Reactivity of Undecenoates and Oleates Toward Thiol Addition

The thiol-ene coupling mechanism has been extensively studied and is known to follow a radical mechanism, in which the addition of a thiyl radical to a double bond is followed by chain transfer to thiol.[35] The thiol-ene addition product is formed, with anti-Markovnikov orientation, with the concomitant generation of a new thiyl radical. Possible termination reactions involve typical radical–radical coupling processes.

$$RS^{\cdot} + CH_2{=}CHR' \rightarrow R{-}SCH_2{-}C^{\cdot}HR' \quad (2)$$

$$R{-}SCH_2{-}C^{\cdot}HR' + HSR \rightarrow RSCH_2{-}CH_2R + RS^{\cdot} \quad (3)$$

Reactivity in the radical thiol-ene reaction can vary considerably depending on the chemical structure of the ene and



SCHEME 1 Synthetic procedure for the preparation of diols.

thiol components. UDA is a monomer with different allylic and vinylic double bond end groups, and OLA is a diolefinic monomer with allylic and internal double bonds. It is logical that the chemical structure of an alkene can significantly affect its reactivity in thiol-ene reactions because of differences in the steric strain and ene susceptibility to thiyl attack and subsequent hydrogen abstraction. It is well known that terminal alkenes react very rapidly and irreversibly with thiols, achieving complete conversions in few minutes.[36,37] The relative reactivity of two UDA end groups toward addition of photoinitiated radical with 2-mercaptoethanol and in the presence of DMPA as photoinitiator was studied, finding that allylic and vinylic chain ends exhibit different reactivities toward thiol addition (about 1.8 less the former against the latter).[32] Presumably, this is due to the presence of an electron-withdrawing group that destabilize the radical intermediate.

Generally, terminal enes are significantly more reactive toward hydrothiolation compared to internal enes. Thus, Hoyle et al.[15] reported that 1-hexene is 8× more reactive

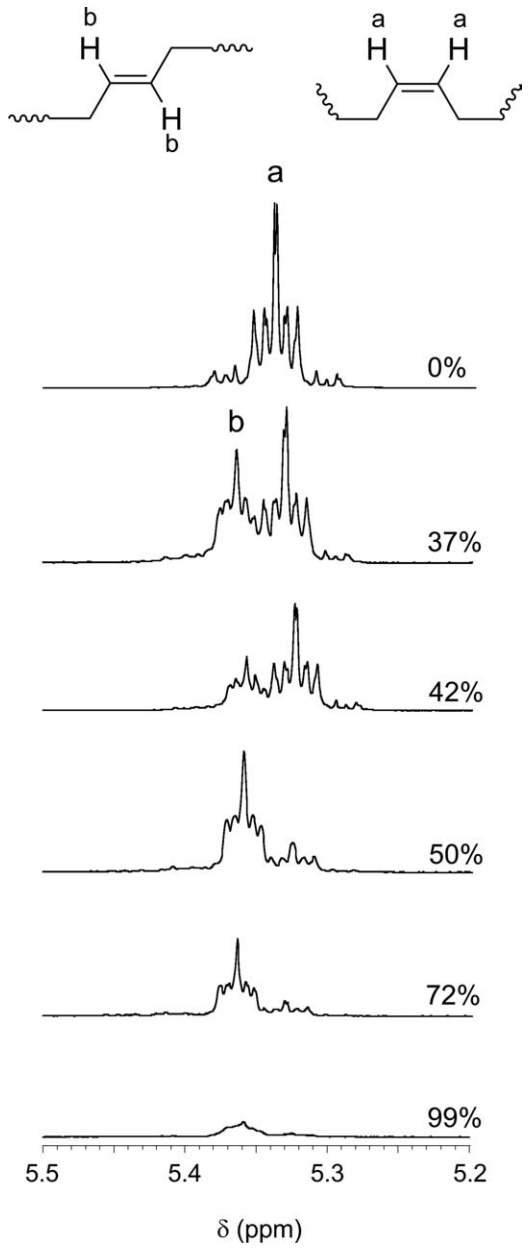


FIGURE 1 Expansion of the 400 MHz ^{1}H NMR spectra during the photoinitiated thiol-ene coupling between 2-mercaptoethanol and methyl oleate.

than *trans*-2-hexene and 18× more reactive than *trans*-3-hexene, clearly highlighting that steric effects are important when considering reactivity. However, these differences in reactivity are not due entirely due to steric effects. As reported previously,[38–41] addition of thyil radical to cis C=C bonds is reversible and is accompanied with an isomerisation process, that is, thyil radicals can be used as means of converting *cis* C=C bonds to trans C=C bonds with high efficiency. A detailed analysis of the ^{1}H NMR spectra during the 2-mercaptoethanol addition to methyl oleate (OLM) confirmed that this process takes place. As shown in Figure 1(a), pure OLM double bond with cis configuration gives signal (a) at around 5.33 ppm. After 5 min (37% conversion), a new signal (b) appears at 5.36 ppm, which is attributed to the chemical shift characteristic of C=C with trans configuration. The appearance of this signal confirms that under these conditions, the addition of a thiyl radical to OLM is a reversible process that generates a more thermodynamically stable trans double bond. After 30 min, at the point of 50% conversion the signal of trans is higher than the cis and at the point of 72% conversion (60 min) only practically the signal of trans ene is remaining. This signal completely disappears after 120 min. This insertion–isomerization–elimination reaction sequence is also responsible for the reduced reactivity observed for OLM.

Following the above considerations, both allyl and methyl undecenoates were reacted with 2-mercaptoethanol in DMPA to yield UDA-diol and UDM-diol, respectively. Also both OLA and OLM yielded OLA-diol and OLM-diol following the procedure described for UDA-diol and UDM-diol but with higher ratio of radical initiator (Scheme 1).

The evolution of the oleic acid to OLA-diol could be followed by ^{1}H NMR (Fig. 2). The spectrum (A) of the initial oleic acid

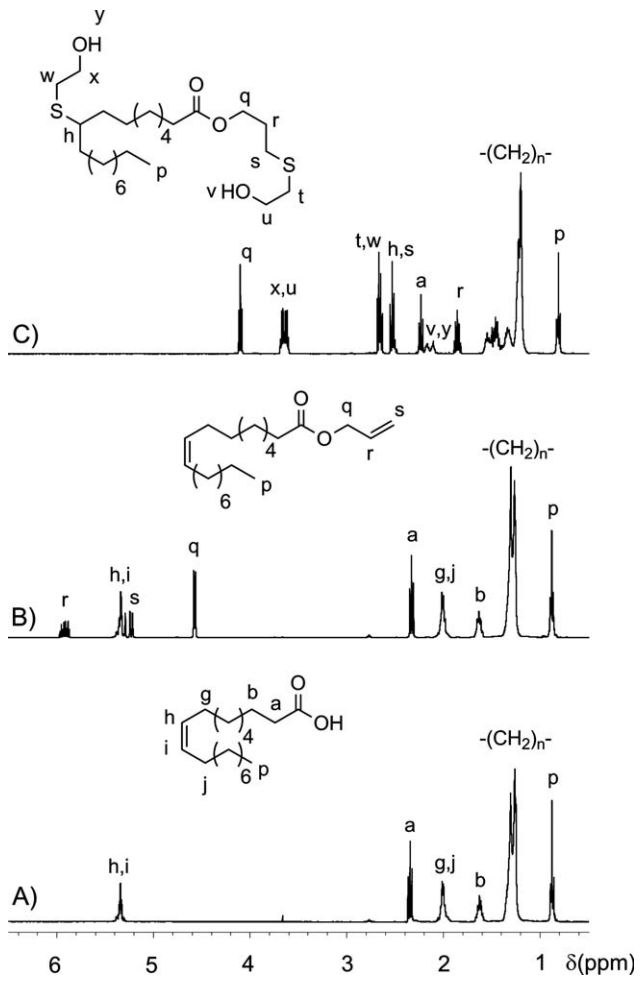


FIGURE 2 ^{1}H NMR spectra of (A) OL; (B) OLA; and (C) OLA-diol.

TABLE 1 Polycondesation Results and Some Properties of PUs

					SEC[c]			Solubility[d]			
PU	Diol	T (°C)	t (h)	Yield (%)	M_n (g/mol)	M_w (g/mol)	M_w/M_n	H_2O	DMSO	$CHCl_3$	THF
PU1[a]	UDM	50	24	99	83,293	188,670	2.1	−	+	−	+
PU2[a]	OLM	50	24	80	36,340	84,050	2.2	−	+	+	+
PU3[a]	UDA	50	24	99	50,930	96,310	1.9	−	+	+	+
PU3′[b]	UDA	40	7	99	71,210	120,820	1.6	−	+	+	+
PU4[a]	OLA	50	24	92	61,860	120,020	1.9	−	+	+	+

[a] Polycondensation reaction carried out in DMF by conventional heating.
[b] Polycondensation reaction carried out in DMF by ultrasound irradiation (42 kHz).
[c] Number and average molecular weights determined by GPC in THF against polystyrene (PS) standards.
[d] Solubility at 25 °C: + soluble, − insoluble.

shows the characteristic signals of the internal C=C at 5.35 ppm. The formation of OLA (spectrum B) is observed for the peaks arising from the methylene next to terminal C=C at 4.58 ppm and the new peaks in the olefinic zone at 5.27 and 5.88 ppm corresponding to protons of terminal C=C. The success of the thiol-ene coupling to yield OLA-diol (spectrum C) was noted from the appearance signals at about 2.4 and 2.6 ppm corresponding to the newly formed carbon–sulfur bonds. More evidence of successful coupling was obtained from the complete disappearance of signals corresponding to alkene protons.

Results obtained in the synthesis of PUs studied in this work as well as some characterization data are given in Table 1. The synthesized undecylenic and oleic acid-based diols (UDM-diol, UDA-diol, OLM-diol, and OLA-diol) were polymerized with MDI in DMF solution at 50 °C for 24 h using tin (II) 2-ethylhexanoate as catalyst. Under these conditions, the reaction proceeded in one step, and isolation and purification of the PUs were carried out by solution–precipitation cycles and subsequent drying under vacuum; yields were in the 80–99% range. Weight-average molecular weights of PUs were in the 36–83 kDa range. Polydispersities oscillated between 2.2 and 1.9 with perceivable differences between those with and without ester groups in the polymer chain. In the case of PU obtained with ultrasound irradiation, the polydispersity was lower.

The chemical structures of PUs were assessed by FTIR and NMR spectroscopy. Characteristic IR absorption bands of main chains were observed. Thus, the C=O stretching bands arising from ester and urethane appear at 1728 and 1701 cm^{-1}, respectively, and the NH stretching and bending bands appear at around 3320 cm^{-1} and 1532 cm^{-1} respectively. ^1H and ^{13}C NMR spectra were in all cases in full concordance with the expected chemical structures of PUs.

The solubility of the PUs is collected in Table 1 for a set of representative solvents evidencing that these compounds have high solubility in all solvents except in water. Only PU1 showed no solubility in $CHCl_3$.

The effect on thermal transitions T_g and T_m arising from the different precursor fatty acid units in the PU chain was investigated by DSC. PUs samples were quenched from the melt to make clear the observation of the glass transition. T_g values measured in such DSC traces are given in Table 2. T_m values were measured on the heating DSC traces recorded PUs samples coming directly from the synthesis and are also given in Table 2. PU1 and PU3 derivatives from undecylenic acid showed higher crystallinity than PU2 and PU4 derivatives from oleic acid. This can be related to the presence of pendant chains in PU2 and PU4, that difficult the packing.

Previously, it was reported that the rates of reaction in the preparation of PUs from H_{12}MDI and different aliphatic diols can be accelerated by the use of high intensity ultrasound.[42] The source of the effect seems to be related to local heating around collapsing cavitation bubbles together with the enhanced mass transfer caused by the fluid motion but it was likely that an effect took place to modify the mode of action of the catalysts in these systems. Hence, we carried out one experience of polymerization of UDA-diol under ultrasonic irradiation. The results shown in Figure 3 and Table 1 allow to confirm that sonochemical reaction proceeded

TABLE 2 Thermal Properties of PUs

	DSC					TGA (°C)		E_a (J/mol)		
	T_g (°C)	T_{m1} (°C)	ΔH_1 (J/g)	T_{m2} (°C)	ΔH_2 (J/g)	$T_{5\%}$	T_{max}	240 °C	250 °C	260 °C
PU1	56	115	17	141	19	274	293/361/463	116	94	97
PU2	28	104	3	–	–	277	284/356/463	151	158	141
PU3	20	124	42	–	–	269	294/362/462	60	71	59
PU4	8	–	–	–	–	290	301/362/459	125	110	127

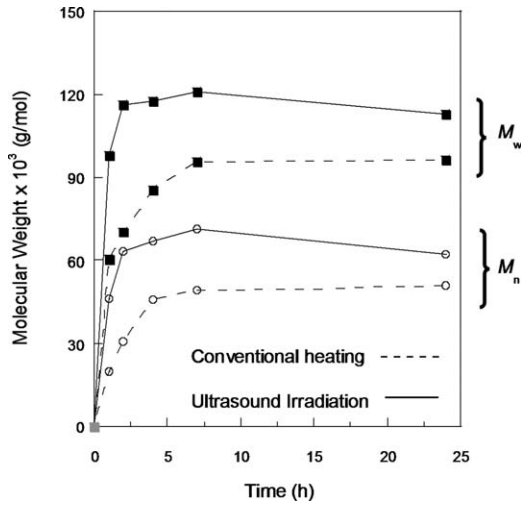


FIGURE 3 Evolution of M_n and M_w versus time under conventional heating and ultrasound irradiation of PU3′.

faster in the early stages and led to higher molecular weight PU compared to PU obtained by conventional thermal polymerization.

The hydrolytic degradability of PUs was evaluated by incubation assays. Neither weight loss nor molecular weight decrease was observed after 6 months. These results are in agreement with the hydrophobic character of all synthesized PUs.

The thermal stabilities of polymers were investigated with TGA in nitrogen stream, and the results are collected in Table 2. All PUs showed three degradation stages and the derivative of the weight loss versus temperature showed three peaks centered at about 300, 360, and 460 °C. The range of temperatures of the first stage suggests that degradation starts at urethane linkages, which takes place through the dissociation to isocyanate and alcohol, the formation of primary amines and olefins, or the formation of secondary amines.[43]

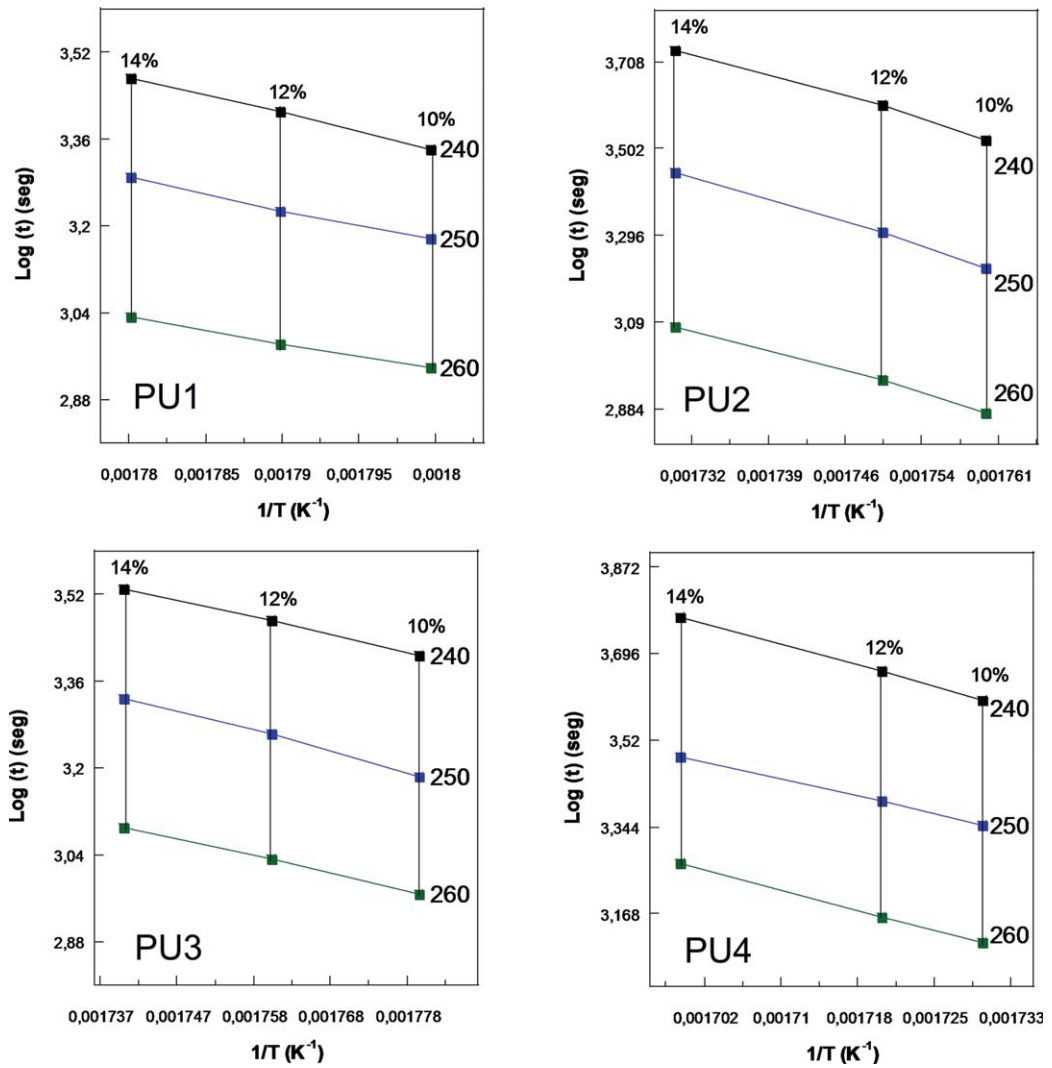


FIGURE 4 Dependence of degradation times in nitrogen on conversion at three temperatures for the polyurethanes.

Degradation kinetic studies for the temperature region of 240–260 °C were carried out. Figure 4 shows the dependence of degradation times in nitrogen on conversion at three different temperatures. Activation energies calculated from the slope of isothermal curves are collected in Table 2. As can be seen, activation energies show dependence on the chemical structure of PUs, being lower for ester group-containing PUs P3 and P4, which should influence the initial degradation step (below 10% conversion) making the degradation process more complex.

Mechanical properties of PUs including tensile strength, modulus, and elongation at break were evaluated from stress–strain curves (Fig. 5). PU4 and PU2 samples show a smooth transition in their stress–strain behavior similar to lightly crosslinked amorphous rubbers. The stress–strain behavior of PU1 and PU3 samples is different showing a yield point as a result of the presence of crystalline domains in these samples which act by increasing the rigidity of the material.

Cytotoxicity of PUs was evaluated using the MTT assay for testing the toxicity of eluates. Figure 6 shows that cell viability was not affected by the presence of extracts from any PU systems within 7 days, reaching values higher than 85% of the control TMX in all polymers. These initial cytotoxicity tests indicate that these materials are promising for biomedical purposes, however, further testing is required to ascertain whether they are biocompatible.

CONCLUSIONS

In this study, we describe a novel route to obtain diols derived from fatty acids. The application of thiol-ene additions to 10-undecenoate and oleate derivatives was carried to obtain the required monomers. The resulting monomers were then polymerized with 4,4′-methylenebis (phenylisocyanate), in DMF solution using tin (II) 2-ethylhexanoate as catalyst, to produce the corresponding thermoplastic PUs (TPUs). Ultrasound irradiation has been proved to improve the PU synthesis. The thus prepared PUs were characterized and revealed good thermal and mechanical properties, making them possible candidates for the substitution of petroleum based materials. MTT test was carried out to asses the potential cytotoxicity of the prepared PUs, indicating no cytotoxic response which indicates that these materials are promising for biomedical purposes.

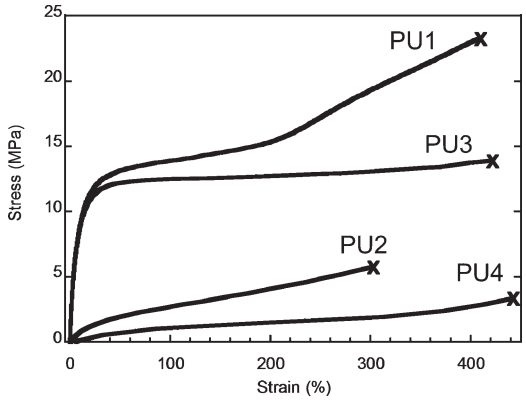


FIGURE 5 Stress–strain curves of the polyurethanes.

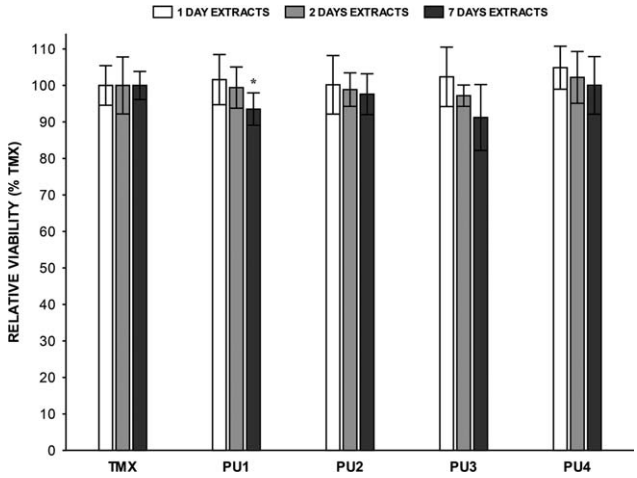


FIGURE 6 MTT cytotoxicity results for control TMX and polyurethanes. Results are the mean ± standard deviation. Statistical analysis ($n = 12$) of each polymer was performed with respect to TMX at a significance level of $*p < 0.05$.

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