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Click Reactivity of Azide-Modified Polyvinyl Chloride as an Entry to Glycopolymer Scaffolds

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Abstract: We report the synthesis of new carbohydrate/triazole polymers based on poly(viny chloride) (PVC). Azide incorporation into commercially available PVC was carried out using nucleophilic substitution and Cu-catalyzed reaction of the resulting PVC-N_3 using three alkynyl-containing acetonide-protected monosaccharides (based on D-glucose and D-galactose) provided a set of PVC-based polymers incorporating a triazolyl linkage with monosaccharide moieties present on the periphery. Modified polymers were characterized by using Fourier transform infrared (FT-IR), Nuclear Magnetic Resonance (^{1}H-NMR and ^{13}C-NMR) spectroscopy, together with thermogravimetric and surface morphological analysis.

Keywords: protected-sugar alkynes, PVC-N_3, click reactions, 1,2,3-triazole.

INTRODUCTION

GLYCOPOLYMERS, synthetic macromolecules carrying carbohydrates, have attracted interest across various topics that have most often included studying a host of biologically important processes, nano biotechnological uses, and drug delivery and biosensor systems.[1] However, glycopolymers are often also biodegradable or offer highly biocompatible ("environmentally-friendly") characteristics and, and particularly when pendant groupings capable of coordinating other species are present, are of interest as remediator agents to sequester pollutants, such as heavy metal contaminants.[2,3]

This type of environmental application ideally requires reagents that possess ease of synthesis, appropriate chemical stability especially within the core polymeric structure, and present chemical functionality necessary for sequestration within a comparatively high density (e.g. dendritic) format. In this case, the function of the carbohydrate component is to provide the bulk polymer with properties, such as aqueous solubility, to enable application in a natural environment.[3,4]

Our goal has been to develop triazole-modified PVC as model glycopolymers since 1,2,3-triazoles have broad biological activities such as antimalarial, antibacterial, antifungal, antiviral, antitumor, anti-inflammatory and anti-Alzheimers.[5–8] Besides pharmaceutical applications, they are frequently used in organic synthesis, polymer chemistry, bioconjugation and material science.[9,10] In this paper we focus on two primary structural elements of a potential sequestration reagent: use of a stable polymer backbone and the nature of the chemical functionality that had to be incorporated as part of the carbohydrate-containing units.[1–4,11]

In terms of the chemical functionality presented, we chose to integrate triazole moieties within the polymer structure as these heterocycles are known to provide a mechanism for strong coordination to metal ions.[10,12,13] Furthermore, these are also units that are also readily accessible via "click reactions" involving high energy components such as azides and alkynes. Originally developed by Huisgen within the context of 1,3-dipolar cycloaddition reactions, the discovery in 2001 by Sharpless of copper (I)-catalyzed 1,3-dipolar cycloaddition (CuAAC) reaction

transformed the range of applications this chemistry can be harnessed for.[14] In particular, the Cu(I)-catalyzed reaction is conducted under very mild conditions (as compared to conventional 1,3-dipolar cycloadditions) and provides high yields of products with commensurate levels of regiocontrol.[9,14,15] As a consequence, CuAAC has been widely applied to azide/alkyne combinations to incorporate functional diversity into a variety of substrates, including glycopolymers and dendrimers.[2,4,15–18]

In order to apply CuAAC, it is necessary to provide the reacting partners: alkyne (or nitrile) and azide. The alkyne component selected was based in ready incorporation of propargyl alcohol into a monosaccharide precursor. The other component was necessarily azide-containing and required an ability to manipulate an existing functionalized polymeric framework. Here our choice of a stable polymer framework was guided by accessibility and cost, and we selected to evaluate modification of polyvinyl chloride (PVC).

PVC is a low cost thermoplastic polymer which was discovered in the early years of the 19th century and that possesses excellent mechanical properties and a high degree of chemical stability and low cost.[19,20] PVC does, however, suffer from poor thermal stability because of the presence of labile chlorine functions present on the skeleton. However, this thermal stability range can be extended by chemical modification of the core polymer, which has been accomplished by using both substitution and elimination. That does enable, for example, an opportunity to exploit reactive halide sites to integrate multiple azides moieties.[21,22] Furthermore, PVC modifications are known to affect key physical parameters and properties, such as surface hydrophilicity, increased wettability, offering low friction surfaces and these modifications can lead to enhanced biocompatibility.[20,23]

Recently, Ouerghui and co-workers used azide-modified PVC (PVC-N_3) to produce polymer-supported triazoles based on click reactivity using alkyl-substituted alkynes.[24,25] These click-modified PVC variants were then able to capture specific ions, such as Cd^{2+}, Pb^{2+}, Cu^{2+}, Ni^{2+}. In 2017, Lamanna *et al.*[10] synthesized two triazole-containing polyvinyl alcohol (PVA) derivatives, one of which also incorporated a protected galactose unit as shown in Figure 1. Again, this involved exploiting the (here hydroxyl) functionality associated with the polymer to allow azide introduction followed by click reaction to incorporate both the triazole ligand and the pendant carbohydrate moiety. Importantly these authors noted that water contaminated with mercury and other heavy metals was cleansed by these modified PVA polymers.

In order to elaborate a PVC scaffold using "click chemistry to incorporate pendant carbohydrate units, such as D-glucose and D-galactose, we required azido

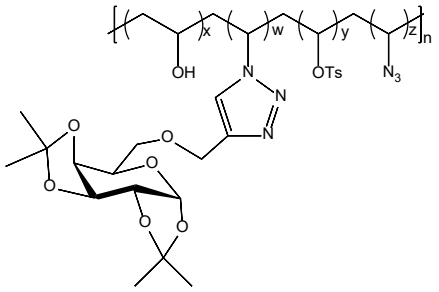


Figure 1. Galactose-based triazolyl PVA (*x*, *w*, *y*, and *z* represent the corresponding carbon chain length).

functionality to be incorporated onto the polymer backbone. This was achieved from commercially available PVC by azide-based nucleophilic substitution according to a literature procedure. This provided PVC-N_3, which was purified by repeated precipitation and the final product was characterized by FTIR (-N_3 present at 2113 cm^{-1}) and elemental analysis, which indicated approximately 10 % incorporation of azide (see below).[9]

The alkyne-based click chemistry partners were based isopropylidene-protected D-glucose and D-galactose units and terminal alkyne groups were incorporated via *O*-alkylation protocols. Finally, CuAAC reaction conditions were used and in this way a set of three PVC-based substrates, incorporating monosaccharide and triazole units, were prepared and characterized by ^{1}H-NMR, thermogravimetric analysis (TGA) and morphological analysis (SEM/EDX) (see supplementary material).

MATERIALS AND METHODS

Chemicals

Polyvinyl chloride (PVC, 98 %, average molecular weight (M_r= 125 000) was supplied from PETKİM-Izmir/Turkey. D-galactose (99 %,) and D-glucose monohydrate (98 %) were purchased from Merck, 3-bromopropyne (80 % in toluene) from Fluka and (+)-sodium L-ascorbate from Acros Organic. Acetone (99 %), dichloromethane (99 %), *tert*-butanol (98 %), *N,N*-dimethyl formamide (DMF, 99 %), methanol (99 %), dimethyl sulfoxide (DMSO, 99 %), trimethylacetyl chloride (99 %), 2,2-dimethoxypropane (DMP, 99 %), sodium azide (98 %), *p*-toluenesulfonic acid (PTSA, 99 %), sulfuric acid (98 %), copper (II) sulfate pentahydrate (99 %) were also purchased from Merck.

Apparatus

Melting points were measured by using Electrothermal 9100 melting point apparatus in capillary and are uncorrected. ^{1}H-NMR (400 MHz) and ^{13}C-NMR (100 MHz) were recorded on Varian AS 400 NMR spectrometer. FT-IR

spectra were recorded on Perkin Elmer FT-IR BX system spectrometer. Optical rotation measurements were carried out on a Rudolph Research Analytical Autopol II automatic polarimeter. Elemental analysis was carried out Elementar Vario MICRO Cube elemental analyzer. Thermal gravimetric analysis (TGA) were performed on Perkin Elmer Diamond TA/TGA with a heating rate of 10 °C min^{-1} under nitrogen (N_2) flow by heating from 20 °C to 600 °C. The morphology of new carbohydrate-containing PVC substrates was analyzed by scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) with ZEISS Gemini 500 equipment. Thin layer chromatography (TLC) and column chromatography were performed on precoated aluminum plates (Merck 5554) and Silica Gel G-60 (Merck 7734), respectively. For chromatogram studies, CH_2Cl_2:MeOH (9 : 1; 8 : 2 and 8.5 : 1.5), PhMe:MeOH (9 : 1) and hexane:EtOAc (3.5 : 1.5) were used. The chromatograms were developed by heating for 2 min after treatment with 5 % aqueous sulfuric acid. All solvent removal was carried out under reduced pressure using a rotary evaporator.

EXPERIMENTAL

Synthesis of PVC-N_3 (2)

PVC (**1**; 1.0 g) was dissolved in dry DMF (30 mL) and NaN_3 (2.0 g; 0.03 mol) was added to this solution. The reaction mixture was stirred at 60 °C for 2.5 hours after which time the mixture was poured into MeOH (150 mL) to give a pale yellow precipitate. The solid was re-precipitated using DMF (to resolubilize) and MeOH (to reprecipitate) three times to give a yellow-orange solid that was dried in air for 2 days, followed by 3 days at 50 °C. IR (KBr) ν_{max}/cm^{-1}; 2113 (-N_3, azide). Anal. found for PVC-N_3 C, 36.27 %; H, 4.76 %; N, 9.99 %. This corresponds to approximately 15 % (which would "require" 9.96 % N) incorporation of azide into the PVC framework.[9]

General Procedure for the Synthesis of D-glucose and D-galactose Precursors[26]

The preparation of 1,2:5,6-di-*O*-isopropylidene-α-D-glucofuranose **(3)** 1,2:3,5-di-*O*-isopropylidene-α-D-glucofuranose **(4)** and 1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranose **(5)** were carried out using literature procedures.

SYNTHESIS OF 1,2;5,6-DI-*O*-ISOPROPYLIDENE-α-D-GLUCOFURANOSE (3), 1,2-*O*-ISOPROPYLIDENE-α-D-GLUCOFURANOSE (3A) AND 1,2:3,4-DI-*O*-ISOPROPYLIDENE-α-D-GALACTOPYRANOSE (5)[26]

Mono-isopropylidene derivative of glucose (1,2;5,6-di-*O*-isopropylidene-α-D-glucofuranose **(3)**) in water phase and di-isopropylidene derivative of glucose in chloroform phase (1,2-*O*-isopropylidene-α-D-glucofuranose **(3a)**) were obtained as a crystalline form by using the literature procedures. For **3**; yield 12 %, m.p. 110 °C (lit. m.p. 110 °C), and for **3a**; yield, 49 %, m.p. 160 °C (lit. m.p. 160 °C). 1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranose **(5)** was obtained as a syrupy product. The yield is 43 %.

SYNTHESIS OF 1,2-O-ISOPROPYLIDENE-6-*O*-(TRIMETHYLACETYL)-α-D-GLUCOFURANOSE (3B)[27]

Obtained as a crystalline solid. Yield is 70 %; m.p. 147–149 °C, (lit. m.p. 145–147 °C); IR (KBr) ν_{max}/cm^{-1}; 1705 (C=O), 3407 (OH), 2876–2979 (CH, aliphatic); ^{1}H-NMR (400 MHz, CD_3OD) δ/ppm: 5.96 (d, 1H, $J_{1,2}$=4.0 Hz, H-1), 4.53 (d, 1H, H-2) 4.24 (m, 1H, H-3 and H-6a), 4.36 (t, 1H, $J_{4,5}$ = 3.2, $J_{3,4}$ = 3.2, H-4), 4.40 (m, 1H, H-5), 4.08 (dd, 1H, $J_{5,6b}$ = 2.8 Hz, H-6b), 3.57 (d, 1H, $J_{3,OH}$ = 3.6 Hz, OH), 3.44 (d, 1H, J = 4.4 Hz, OH) 1.32, 1.48 (s, 6H, -CH_3, isopropyl group), 1.23 (s, 9H, pivaloyl group).

SYNTHESIS OF 1,2:3,5-DI-O-ISOPROPYLIDENE-6-*O*-(TRIMETHYLACETYL)-α-D-GLUCOFURANOSE (3C)[27]

Obtained as a syrupy product. Yield is 90 %; ^{1}H-NMR (400 MHz, CD_3OD) δ/ppm: 5.94 (d, 1H, $J_{1,2}$ = 4.0 Hz, H-1), 4.55 (d, 1H, H-2), 4.15 (m, 1H, $J_{3,4}$ = 4.0, H-3), 4.24 (dd, 1H, $J_{4,5}$ = 7.2, H-4), 3.66 (ddd, 1H, $J_{5,6a}$ = 4.0, $J_{5,6b}$ = 7.2, H-5), 4.20 (dd, 1H, $J_{5,6a}$ = 12.0, H-6a), 4.09 (dd, 1H, $J_{6a,6b}$ = 12.0, H-6b), 1.23, 1.24, 1.29, 1.37 (s, 12H, -CH_3, isopropyl groups), 1.13 (s, 9H, pivaloyl group).

SYNTHESIS OF 1,2:3,5-DI-*O*-ISOPROPYLIDENE-α-D-GLUCOFURANOSE (4)[27]

Obtained as a syrupy pure product in a light-yellow color. Yield is 73 %; ^{1}H-NMR (400 MHz, DMSO-d_6) δ/ppm: 5.92 (d, H, $J_{1,2}$ = 3,6 Hz, H-1), 4.53 (d, 1H, H-2), 4.08 (d, 1H, $J_{3,4}$ = 4,0 Hz, H-3), 4.21 (dd, 1H, $J_{4,5}$ = 5,4 Hz, H-4), 3.45-3.54 (m, 3H, H-5, H-6a and H-6b), 4.80 (s, 1H, OH), 1.37, 1.28, 1.25, 1.23 (s, 12H, -CH_3, isopropyl groups); ^{13}C-NMR (100 MHz, $CDCl_3$) δ/ppm: 111.8–106.3 (2×$\underline{C}(CH_3)_2$), 100.7 (C-1), 83.9, 79.2, 75.2, 73.3, 62,6 (C-2, C-3, C-4, C-5 and C-6), 27.5,27.0,24.8,24.7 (4 × $\underline{C}H_3$).

SYNTHESIS OF 1,2:5,6-DI-*O*-ISOPROPYLIDENE-3-*O*-(2-PROPYN-1-YL)-α-D-GLUCOFURANOSE (6)[28]

To an ice-cold solution of 1,2:5,6-di-*O*-isopropylidene-α-D-glucofuranose (**3**; 1.3 g; 0.005 mol) in DMF (5 mL) under argon (N_2) was added a suspension of NaH (0.24 g; 0.01 mol) in DMF (10 mL) (**CAUTION**). After evolution of hydrogen had ceased, 3-bromopropyne (80 %, 0.58 mL, 0.0064 mol) was added slowly and the mixture maintained at ice-bath temperature for 3 h. After this time, cold water was added carefully and the mixture was extracted with diethyl ether (Et_2O; 3 × 25 mL). The extracts were washed with distilled water (2 × 20 mL) and brine (2×20 mL), then dried (Na_2SO_4). Removal of solvent and purification of the

residue by column chromatography (using CH_2Cl_2 as eluent) gave **6** (0.9 g, 60 %) as a pale yellow oil. $[\alpha]D$ = –12.00 (*c* 0.5 $CHCl_3$); IR (KBr) ν_{max}/cm^{-1}; 3274 (C≡C-H), 2116 (C≡C), 2896-2988 (CH, aliphatic); ^{1}H-NMR (400 MHz, $CDCl_3$) δ/ppm: 5.88 (d, 1H, $J_{1,2}$ = 3.6 Hz, H-1,) 4.62 (d, 1H, H-2) 4.30–4.24 (m, 3H, H-3, H-5 and -O-C$\underline{H}_2$) 4.14 (dd, 1H, *J* = 3.2 Hz, *J* = 7.6 Hz, H-4) 4.07-4.1 (m, 3H, H-6a and -O-C$\underline{H}_2$-) 3.99 (dd, 1H, $J_{5,6b}$ = 5.6 Hz, $J_{6a,6b}$ = 8.6 Hz, H-6b) 2.47 (t, 1H, $J_{H,CH2}$ = $J_{H,CH2}$ = 2.4 Hz, C≡C$\underline{H}$) 1.50, 1.43, 1.35, 1.32 (4 x s, 12H, -CH_3, isopropyl groups).

SYNTHESIS OF 1,2:3,5-DI-*O*-ISOPROPYLIDENE-6-*O*-(2-PROPYN-1-YL)-α-D-GLUCOFURANOSE (7)[28]

Using the same procedure as described for **3**, 1,2:3,5-di-*O*-isopropylidene-α-D-glucofuranose **(4)** was *O*-alkylated to give, after purification by chromatography (hexane:EtOAc; 95:5), **7** (10.5 g, 72 %) as a pale yellow solid. m.p. 33–35 °C; $[\alpha]D$ = +24.0 (*c* 0.5 $CHCl_3$); IR (KBr) ν_{max}/cm^{-1}; 3270 (C≡C-H), 2112 (C≡C), 2870-2988 (CH, aliphatic); ^{1}H-NMR (400 MHz, DMSO-d_6) δ/ppm: 5.94 (d, 1H, $J_{1,2}$=3.6 Hz, H-1), 4.54 (d, 1H, H-2), 4.12 (d, 1H, $J_{3,4}$ = 3.6 Hz, H-3), 4.21 (dd, 1H, $J_{4,5}$ = 7.0 Hz, H-4), 4.22 (dd, 2H, J_{CH2} = 1.2 Hz, $J_{CH2C\equiv CH}$ = 2.4 Hz, -O-C$\underline{H}_2$-), 3.51–3.62 (m, 3H, H-5, H-6a and H-6b), 2.48 (t, 1H, $J_{H,CH2}$ = $J_{H,CH2}$ = 2.0 Hz, -C≡CH), 1.37, 1.28, 1.25, 1.23 (4 x s, 12H, -CH_3, isopropyl groups); ^{13}C-NMR (100 MHz, $CDCl_3$) δ/ppm: 112.3, 106.5 (2x$\underline{C}(CH_3)_2$), 101.1 (C-1), 79.60, 79.61 ($CH_2\underline{C}$≡CH and $CH_2C\equiv\underline{C}H$), 58.9 ($\underline{C}H_2C\equiv CH$), 84.1, 75.01, 75.04, 71.56, 70.3 (C-2, C-4, C-3, C-5 and C-6), 27.3, 26.7, 24.2, 24.1 (4×$\underline{C}H_3$).

SYNTHESIS OF 1,2:3,4-DI-*O*-İSOPROPYLİDENE-6-*O*-(2-PROPYN-1-YL)-α-D-GALACTOPYRANOSE (8)

Using the same procedure as described for **3**, 1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranose **5** was *O*-alkylated to give, after purification by chromatography (CH_2Cl_2), **8** (12.3 g, 83 %) as a light-yellow solid. m.p. 62-63 ºC; $[\alpha]D$ = –72.0 (*c* 0.5 $CHCl_3$); IR (KBr) ν_{max}/cm^{-1}; 3256 (C≡C-H, alkyne), 2112 (C≡C), 2864-2988 (CH, aliphatic); ^{1}H-NMR (400 MHz, $CDCl_3$) δ/ppm: 5.53 (d, 1H, $J_{1,2}$ = 5.2 Hz, H-1), 4.31 (dd, 1H, $J_{2,3}$ = 2.4 Hz, H-2), 4.61 (dd, 1H, $J_{3,4}$ = 7.6 Hz, H-3), 4.26 (dd, 1H, $J_{4,5}$ = 2.0 Hz, H-4,), 3.99 (ddd, 1H, $J_{5,6a}$ = 5.2 Hz, $J_{5,6b}$ = 7.2 Hz, H-5), 3.77 (dd, 1H, $J_{6a,6b}$ = 10.0 Hz, H-6a), 3.67 (dd, 1H, H-6b), 4.22 (dd, 2H, J_{CH2} = 7.6 Hz, $J_{CH2C\equiv CH}$ = 2.4 Hz, -O-C$\underline{H}_2$-), 2.43 (t, 1H, $J_{H,CH2}$ = $J_{H,CH2}$ = 2.4 Hz, C≡CH)1.54, 1.45, 1.34, 1.33 (4 x s, 12H, -CH_3, isopropyl groups); ^{13}C-NMR (100 MHz, $CDCl_3$) δ/ppm: 109.5, 108.7 (2×$\underline{C}(CH_3)_2$), 96.5 (C-1), 79.9 ($CH_2\underline{C}$≡CH), 74.8 ($CH_2C\equiv\underline{C}H$), 58.6 ($\underline{C}H_2C\equiv CH$), 71.3, 70.9, 70.7, 68.9, 66.9 (C-2, C-3, C-4, C-5 and C-6), 26.2, 26.1, 25.1, 24.6 (4×$\underline{C}H_3$).

General Procedure for the "Click Reaction" of Alkynes 6–8

$CuSO_4.5H_2O$ (0.005 g; 2.01×10^{-5} mol) and (+)-sodium L-ascorbate (0.02 g; 1.0×10^{-4} mol) were added to a solution of PVC-N_3 (**2**; 0.1 g) in DMF (10 mL). In separate reactions, alkyne derivatives (**6, 7** and **8**; 0.001 mol) were added to the polymer solution and the resulting suspensions were stirred slowly at 50 °C. Reaction progress was monitored by FTIR and once loss of the azide peak at approximately 2100 cm^{-1} was complete, the mixture was poured into methanol (50 mL). The precipitate was isolated by filtration, washed with $NH_{3(aq)}$ (50 mL) and EDTA (0.1 M, 50 mL) to provide the PVC-modified polymers, which were assigned as 1,2:5,6-diisop-**D**-GluFuran-1,2,3-triazole-PVC **(9)**, 1,2:3,5-diisop-D-GluFuran-1,2,3-triazole-PVC **(10)** and 1,2:3,4-diisop-D-GalPyran-1,2,3-triazole-PVC **(11)**.

CHARACTERIZATION OF 1,2:5,6-DIISOP-D-GLUFURAN-1,2,3-TRIAZOLE-PVC (9)

Obtained as a pale brown-yellow amorphous solid. IR (KBr) ν_{max}/cm^{-1}; 3142 (CH, triazole ring), 2878-2990 (CH, aliphatic), 1552 (C=N), 1434-1332 (CH, aliphatic), 1100-1044 (CH, aromatic); ^{1}H-NMR (400 MHz, DMSO-d_6) δ/ppm: 7.95 (s, 1H, C$\underline{H}$=N), 5.82 (s,1H, H-1), 4.63, 4.40, 3.93 (m, 6H, H-2, H-3, H-4, H-5 and H-6) 1.38, 1.31, 1.24 (s, 12H, -CH_3, isopropyl groups), 2.89 and 2.73 (PVC backbone).

CHARACTERIZATION OF 1,2:3,5-DIISOP-D-GLUFURAN-1,2,3-TRIAZOLE-PVC (10)

Obtained as a pale brown-yellow amorphous solid. IR (KBr) ν_{max}/cm^{-1}; 3142 (CH, triazole ring), 2858-2956 (CH, aliphatic). 1436-1386 (CH, aliphatic), 1170-1080 (CH, aromatic); ^{1}H-NMR (400 MHz, DMSO-d_6) δ/ppm: 8.30 (s, 1H, C$\underline{H}$=N), 5.93 (s, 1H, H-1), 4.54, 3.60, 3.50 (m, 6H, H-2, H-3, H-4, H-5 and H-6), 1.37 and 1.25 (s, 12H, -CH_3, isopropyl groups), 2.89 (PVC backbone).

CHARACTERIZATION OF 1,2:3,4-DIISOP-D-GALPYRAN-1,2,3-TRIAZOLE-PVC (11)

Obtained as a pale brown-yellow amorphous solid. IR (KBr) ν_{max}/cm^{-1}; 3142 (CH, triazole ring), 2878-2990 (CH, aliphatic), 1434-1384 (CH, aliphatic), 1166-1078 (CH, aromatic); ^{1}H-NMR (400 MHz, DMSO-d_6) δ/ppm: 8.27 (s, 1H, C$\underline{H}$=N), 5.43 (s, 1H, H-1), 4.55 and 4.32 (m, 6H, H-2, H-3, H-4, H-5 and H-6), 1.42, 1.33, 1.26 (s, 12H, -CH_3, isopropyl groups), 2.89 and 2.73 (PVC backbone).

RESULTS AND DISCUSSION

Our objective was to prepare carbohydrate-based PVC polymers containing triazole rings, for application as robust and biocompatible for use in remediation of environments contaminated by heavy metal species. For this purpose, we functionalized PVC by partial chloride/azide exchange to provide PVC-N_3, which was then subjected to Sharpless-based Cu-catalyzed click reaction with a set of readily available *O*-propargyl derivatives of D-glucose and D-galactose.

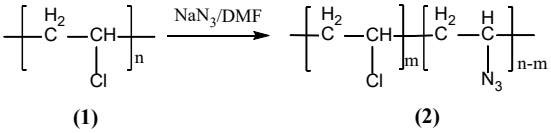
This resulted in the formation of a set of new triazole-linked carbohydrate-containing PVC-derivatives with the triazole ring generated *via* 1,3-dipolar cycloaddition and the periphery expressing isopropylidine-protected monosaccharide units based on D-glucose and D-galactose.

Spectroscopic Characterization of PVC-N_3 and PVC-based Glycopolymers

Our first task was to functionalize commercially-available PVC **1** with azide and this was achieved by nucleophilic substitution using NaN_3 in DMF (Scheme 1).

The IR spectrum of PVC-N_3 **2** (dark blue) is shown in Figure 2. Key is the presence of a strong band at 2113 cm^{-1} assigned to the azido group. The ^{1}H-NMR spectrum of PVC-N_3 **2** is less diagnostic given the similarities associated with -Cl and -N_3, however, a more quantitative assessment of the extent of functionalization was obtained using elemental analysis. Using the percentage of nitrogen, we estimate approximately 10–15 % azide incorporation was achieved under the displacement conditions used.

The requisite monosaccharide units **6**–**8** had been prepared using literature methods where the alkyne moiety had been introduced selectively via *O*-propargylation of a bis(isopropylidine) protected variant (**3**–**5**). Using the alkyne IR shift (2116 cm^{-1}) as another monitoring tool we carried out click reactions with these carbohydrate-based alkynes and PVC-N_3 **2** to give PVC-modified sugar-based polymers (Scheme 2). In this way 1,2:5,6-diisop-D-GluFuran-1,2,3-triazole-PVC **(9)**, 1,2:3,5-D-GluFuran-diisop-1,2,3-triazole-PVC **(10)** and 1,2:3,4-diisop-D-GalPyran-1,2,3-triazole-PVC **(11)** were obtained and characterized.



Scheme 1. Synthetic pathway of PVC-N_3 2.

It is appropriate, however, to discuss the optimization of this process that we conducted. Our initial experiments to achieve CuAAC involving PVC-N_3 **2** were done at room temperature and while reaction occurred, this required several days to go to completion. When these reactions were repeated at 50 °C we observed a much faster transformation ranging from 26 hours to 4 hours. However, the main factor determining reaction rate was the structure of the carbohydrate component and, we deduce, the accessibility of the alkyne moiety. The more hindered substrates **6** and **7** required reaction times of 26 and 18 hours, respectively, at 50 °C whereas with pyranose **8** reaction was complete (see below) after 4 hours.

FT-IR, using the characteristic azide peak at 2113 cm^{-1}, provided a convenient and effective tool for monitoring the progress of CuAAC reactions. Loss of this peak indicated consumption of PVC-N_3 **2** and at this point, the reactions were quenched with methanol in order to precipitate the crude polymer. Subsequent purification primarily involved washing several times by aqueous ammonia followed by aqueous EDTA to remove Cu^{2+} residues to provide the target sugar-based triazolyl PVC substrates **9**–**11** as amorphous solids and this is summarized in Scheme 2.

We were able to obtain satisfactory IR and ^{1}H-NMR spectra using DMSO of polymers **9**–**11** to confirm structural identify, however, a lack of sufficient solubility (even in DMSO) precluded acquisition of ^{13}C-NMR data. The ^{1}H-NMR spectrum of polymer **9** is shown in Figure 3.

FTIR studies (Figure 2) indicated characteristic signals at 3142 cm^{-1} (-CH) and at 1552 cm^{-1} (-C=N-, triazole). The extinction of the specific peaks of the alkyne groups observed at between 3250–3270 cm^{-1} and 2112–2116 cm^{-1} and the detection of the characteristic peaks for -C-H and for -C=N- groups on the triazole ring, respectively, at 3142 cm^{-1}

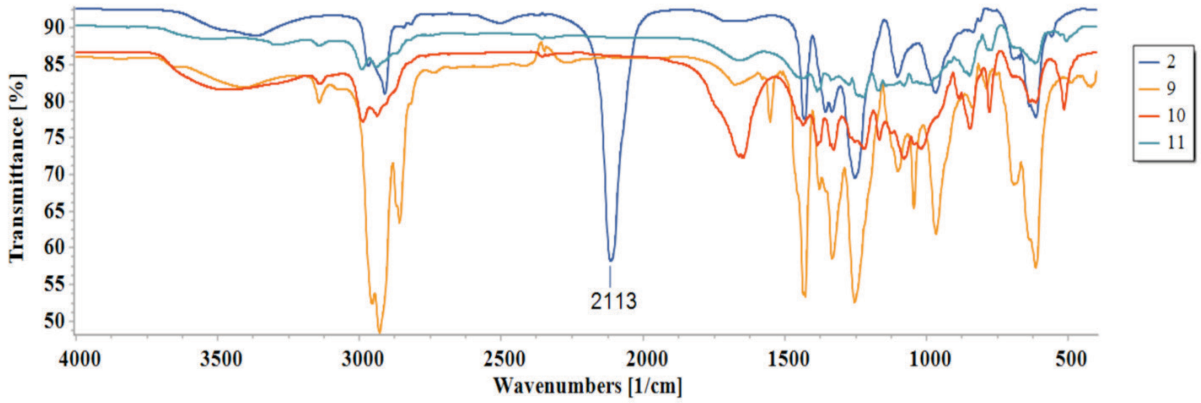
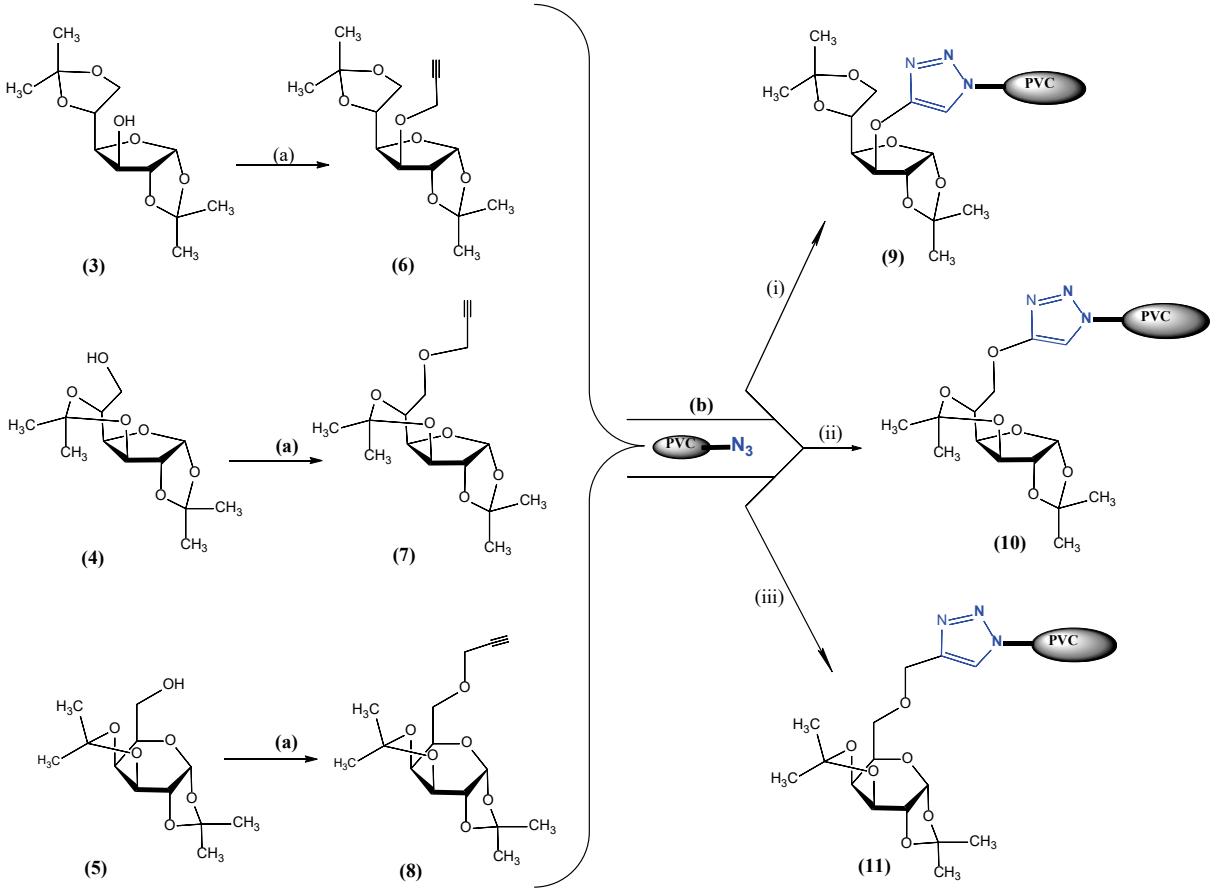


Figure 2. Superimposed FT-IR spectra of PVC-N_3 2 and sugar modified PVC substrates (9, 10, 11).



Scheme 2. Synthesis of terminal alkyne derivatives of D-glucose and D-galactose protected with isop-groups and Click reactions of compound **6**, **7**, and **8** with PVC-N_3. Reagent and conditions for **a**: 3-Bromopropyne (1.3 equiv.), NaH (5.0 equiv.) in DMF, under N_2 atmosphere, 0 °C, 2 h. Reagent and conditions for **b**: alkyne derivatives (**6, 7, 8**; 0.001 mol), PVC-N_3 (0.1 g), $CuSO_4 \cdot 5H_2O$ (10 %), (+)-sodium L-ascorbate (25 %) in DMF (i) 50 °C, 26 h (ii) 50 °C, 18 h (iii) 50 °C, 4 h.

and 1552 cm^{-1} served to support the structural assignments presented here.

Furthermore, ^{1}H-NMR spectra (carried out in DMSO solution) provided further support. The anomeric protons for polymers **9**, **10** and **11** were observed at 5.82, 5.94 and 5.43 ppm, respectively and the characteristic C(5)-H of the triazole appeared at 7.95, 8.30 and 8.27 ppm confirmed that the CuAAC reaction had been successful.[9,10,29]

Thermogravimetric Analysis of 9–11

Thermogravimetric (TG) characteristics of the PVC-based glycopolymer models (**9, 10** and **11**) were measured, together with the corresponding (reference) profiles of the starting PVC and PVC-N_3, in the temperature range of 20–600 °C, by heating at 10 °C min^{-1} under nitrogen (2.5 mL min^{-1}) (Figure 4). The starting polymer (PVC) showed two decomposition transitions: 200–380 °C which we attribute to dehydrochlorination and 380–500 °C which we associated with a more fundamental breakdown of the polymer backbone.[30] The first degradation step proceeds at a rate similar to the other substrates studied while the second degradation step proceeds more slowly, leaving approximately 17 % of mass at 600 °C. On the other hand, the thermal degradation of PVC-N_3 **2** also took place in two steps. It has the first distinctive decomposition between 200 and 350 °C. Its second decomposition is between 380 and 520 °C, leaving about 8 % residue. The initial decomposition is rapid, initiates at 200 °C and the maximum degradation rate temperature is 280 °C. This is very similar to PVC **1** but the second transition is less marked, suggestion that the thermal stability of the polymer decreases considerably with the introduction of azide (Table 1).

As seen in Figure 4, in the case of polymer models **9–11**, the initial degradation temperature decreases in comparison to the unglycosylated polymers, PVC and PVC-N_3. However, within that set of three substrates, similar TGA characteristics were observed where the first step is faster than the second. Of the three glycosylated polymers, the glucopyranose variant **10** is the most thermally stable (with initiation of decomposition at > 220 °C) while **9** and **11**

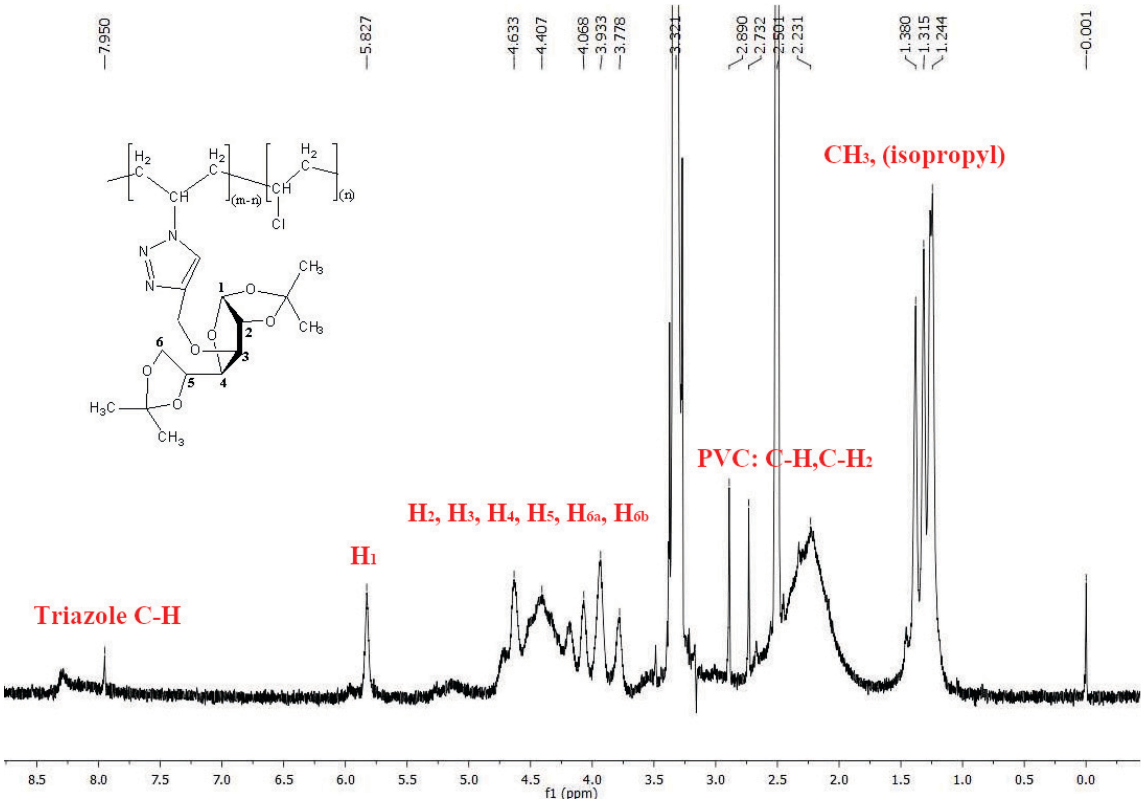


Figure 3. ^{1}H-NMR spectrum of polymer **9**.

Table 1. TGA outcomes of parent polymers (PVC **1** and PVC-N_3 **2**) and glycosylated polymers (**9**, **10** and **11**) based on PVC M_r = 125 000.

Polymer compounds	t_5 (°C)	$t_{10\%}$ (°C)	$t_{50\%}$ (°C)	Weight loss (%) at 500 °C / max residue (%)
1	264	275	323	82/18
2	264	270	307	90/10
9	194	198	263	71/29
10	202	224	282	79/21
11	188	195	264	69/31

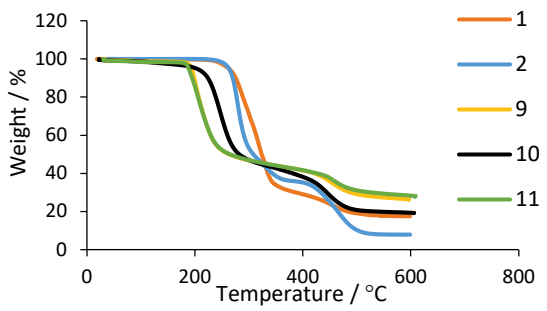


Figure 4. Superimposed TGA curves of PVC (**1**), PVC-N_3 (**2**) and glycosylated polymers (**9**, **10** and **11**).

started to breakdown below 180 °C. All monosaccharide-containing polymers had decomposition initiation temperatures less than the parent polymers (**1** and **2**) but at higher temperatures showed equivalent or somewhat better structure stability.

SEM-EDX Analysis of 9–11

An energy-dispersive X-Ray (EDX or EDS) analysis helps to gain information for material characterization and SEM-EDX multi-systems provide a valuable means understanding morphology and molecular structure characteristics of polymeric compounds. SEM photographs of PVC **1**, PVC-N_3 **2** and glycopolymer models **9–11** are shown in Figure 5. PVC **1** (Figure 5, Image 1) shows regular and round-shaped while the image from PVC-N_3 **2** (Image 2) showed significant deterioration as evidenced by a crushed/fragmented morphology with a significantly increased surface area. Additionally, the SEM photographs of glycopolymers **9**, **10**, and **11** showed that both the occurrence of particle size reductions and chain-like shapes were present. The surface appearance of SEM resembles the fiber structures for substrates **9** and **10**. The SEM morphology of polymer **11** aggregates into irregular particles with different sizes. These highly detected visible shape changes of SEM images proved that sugar molecules exposed to various mixing and heating processes with the parent polymer PVC-N_3 were suspended

to PVC as targeted pendants. SEM microphotographs of the new glycopolymer models with their parents were represented in Figure 5 in detail.

EDX provides information on the chemical compositions and elemental distribution within a sample. The EDX image and the element type graphic result are

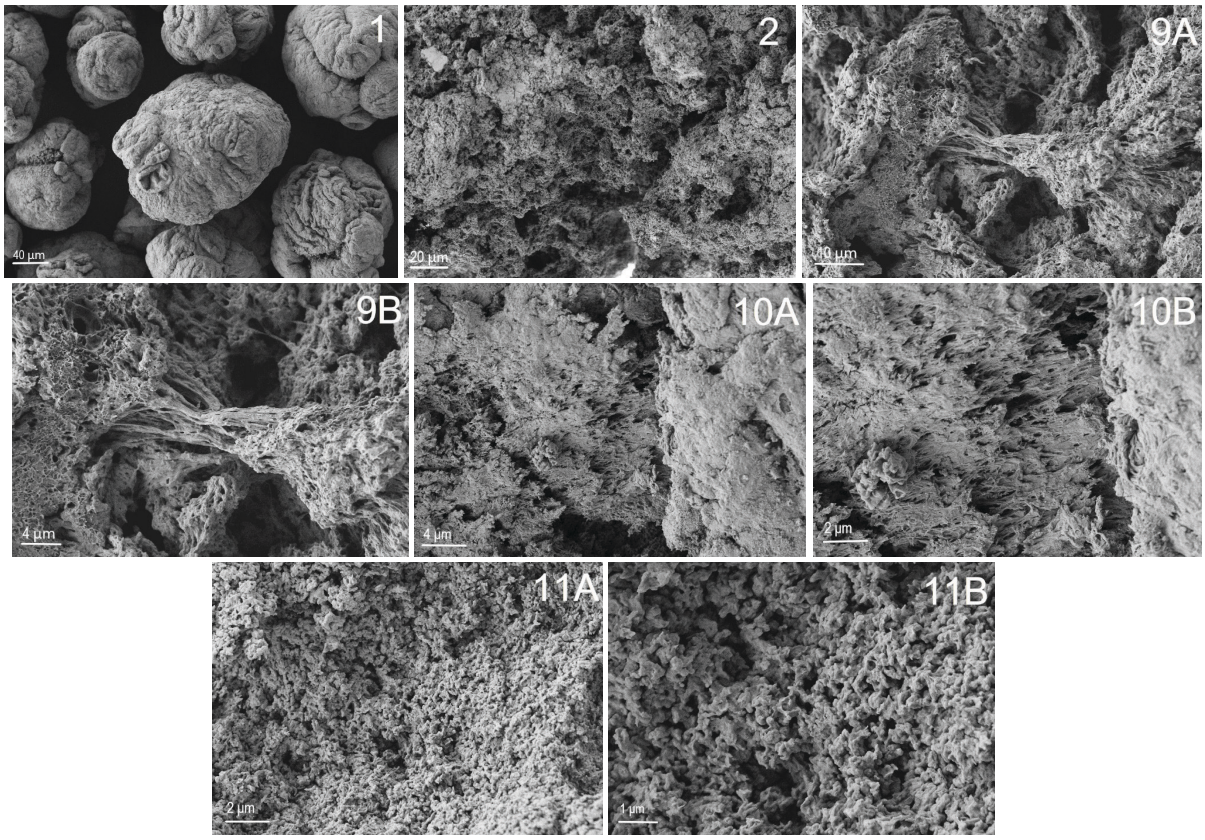


Figure 5. SEM microphotographs of parent polymers (**1** and **2**) and the new PVC-modified glycopolymer models (**9**, **10** and **11**). Image 1 = PVC; Image 2 = PVC-N_3; Images 9A and 9B = 1,2:5,6-diisop-D-GluFuran-1,2,3-triazole-PVC **9**; Images 10A and 10B = 1,2:3,5-D-GluFuran-diisop-1,2,3-triazole-PVC **10**; Images 11A and 11B = 1,2:3,4-diisop-D-GalPyran-1,2,3-triazole-PVC **11**.

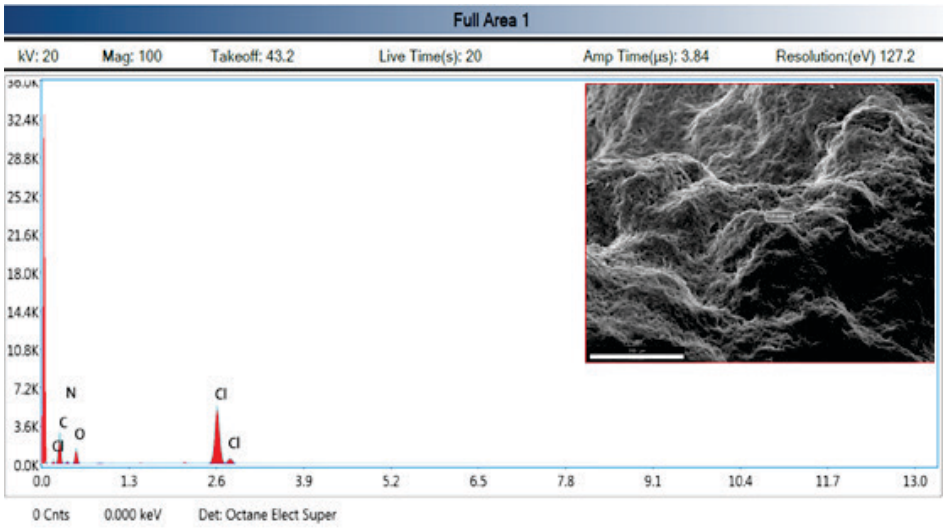


Figure 6. Element contents and EDX image of PVC-modified glycopolymer model **9**.

Table 2. Elemental composition *via* EDX analysis.

Polymers	Elements (%)					
	C	Cl	O	N	O : N	Na
1	90.86	9.14	–	–	–	–
2	68.64	8.71	–	22.65	–	–
9	58.17	6.86	23.87	8.41	2.84[(a)]	2.68[(b)]
10	66.39	8.25	16.96	8.39	2.03[(a)]	–
11	59.89	3.54	22.99	13.58	1.69[(a)]	–

[(a)] The calculated O : N ratio based on complete conversion of azide to a carbohydrate-substituted triazole is 2.28 in each case.
[(b)] Sodium is presumed to arise from use of sodium ascorbate in the click reaction.

presented here for PVC-modified glycopolymer model **9** (Figure 6) and elemental percentages of all polymers achieved from EDX results are shown in Table 2. The elemental composition is again consistent with successful CuAAC reaction to incorporate carbohydrate units onto an azide- modified PVC backbone. In the EDX analysis results, the presence of the oxygen elements which are found in approximately 20 % for compounds **9**, **10**, and **11** proved the sugar units as a pendant on PVC-N_3 parent.

CONCLUSIONS

This study aimed to synthesize the new triazole-linked carbohydrate-containing polymers by incorporation of glucofuranose and galactopyranose units onto an azide-modified PVC backbone using "click chemistry". Use of commercially available PVC followed by incorporation of azide residues and the ready availability of *O*-propargyl protected monosaccharide moieties allowed for use efficient and selective "click reactions" as an efficient entry to novel triazole-containing PVC substrates. Both azide functionalization and click reactions were readily followed using FTIR and the resulting products were of interest as reagents to sequester heavy metal pollutants. Polymers have been characterized by FTIR and ^{1}H-NMR but issues with solubility precluded acquisition of ^{13}C NMR data and elemental composition (using EDX) is consistent with good to very good levels of conversion and with the assignments made. Thermogravimetric analysis (and comparison with PVC itself) shows that while thermal decomposition is initiated at a lower temperature, the structural integrity of the derivatized PVC polymers is not dramatically different to PVC itself.

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Supplementary Information. Supporting information to the paper is attached to the electronic version of the article at: https://doi.org/10.5562/cca3883.

PDF files with attached documents are best viewed with Adobe Acrobat Reader which is free and can be downloaded from Adobe's web site.

Dedicated to my dear mother Necmiye Yenil, to whom I wish a speedy recovery.

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