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Extremely Rapid and Versatile Synthesis of High Molecular Weight Step Growth Polymers via Oxime Click Chemistry

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Extremely rapid step growth polymerization was achieved using an oxime click chemistry approach. The highly efficient oxime reaction resulted in the synthesis of 35 kDa polymers within 5 minutes at 60℃ and 32 kDa polymers within 13 minutes at room temperature and, by altering the monomer ratio, polymers were synthesized with controlled end-group chemistry. Furthermore, the versatility of this chemistry was demonstrated by polymerisation of functional (bipyridine and boronic acid functional) monomers. The very rapid formation, extremely benign reaction conditions, functional group tolerance and high molecular weights obtained indicate the potential of oxime chemistry as a versatile tool for step-growth polymer synthesis.

Step-growth polymerization is used to prepare some of the most important materials in modern society including polyesters, polyamides, polyurethanes and polycarbonates; materials which are used as textiles, plastics and a variety of other products.[1] In modern society step-growth polymers have an enormous industrial, environmental, economic and social impact. However, despite their importance, their synthesis still utilises relatively harsh conditions; often requiring the use of high temperatures (above 250°C for the synthesis of polyethylene terephthalate)[2] or pressures, environmentally unfriendly materials or solvents (use of phosgene in polycarbonate and polyurethane production),[3, 4] or the use of metallic catalysts.[5] The development of new pathways to synthesise step-growth polymers under more benign conditions promises massive economic and environmental benefits and will greatly expand the scope of these important materials.

The introduction of click chemistry in 2001 by Sharpless *et al.*,[6] traditionally used for the synthesis of small molecules, has more recently been adopted by polymer chemists for the synthesis of high molecular weight step-growth polymers.[7-20] By definition, click reactions must be modular, wide in scope, give very high yields, generate only inoffensive by-products and have a single reaction trajectory.[6] These characteristics make click chemistry the ideal choice for the synthesis of next generation step-growth polymers.

Currently, research on click-polymers is focused mainly on the copper catalysed azide-alkyne cycloaddition (CuAAC)[7-11] and thiol-ene reactions,[12-16] although other click reactions have proven versatile tools for polymer synthesis[17-21]. Generally, click polymerizations are reported to take anywhere from several hours to several days and often require high temperatures (anywhere from 30 - 150°C) or, in the case of the CuACC reaction, the use of metal catalysts. Recently, the Sharpless group reported a new, scalable and versatile example of step-growth polymers being formed via the sulfate click reaction.[22] The conditions for this polymerization are mild (2 hours at 150°C); however this inspired us to develop an efficient step growth polymerization with even less stringent conditions.
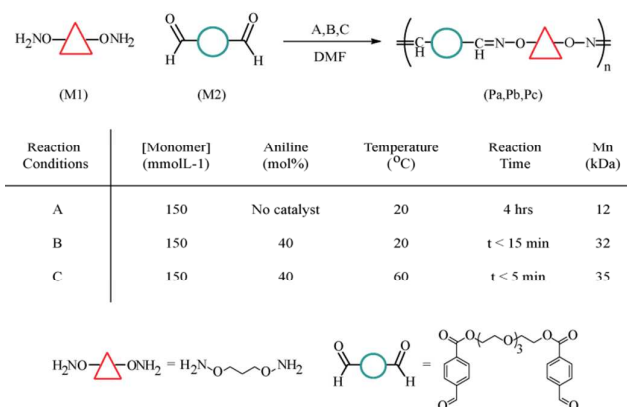
The use of carbonyl chemistry, namely the formation of imine, hydrazone and oxime bonds, for materials chemistry has grown in popularity due to the highly efficient reactions, biomolecular orthogonality and dynamic nature of the bonds. Imine chemistry has been used for the functionalization of polymers[23] and both imine and hydrazone chemistry has been used for the development of dynamic polymers.[19, 24]

We identified the oxime click reaction as a potential means of rapid step-growth polymer synthesis under benign reaction conditions. The oxime bond has found utility in bioconjugation[25-27] as it is highly efficient, biorthogonal, occurs in aqueous solvents and forms water as the only by-product. Recently, oxime chemistry has been developed for various materials science applications, such as drug delivery[28, 29] and surface patterning,[30, 31] but has found minimal use in polymer chemistry, being mainly utilised for hydrogel synthesis[32-34] and as a means of functionalising polymer post-synthesis.[35-37] The popularity of oxime chemistry in materials science is growing quickly however due to the very high efficiency of oxime formation and the dynamic nature of the bond. Within the last year, self-healing hydrogels,[38] dynamic polymers[39] and bio-adhesives have been developed which make

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use of the attractive properties of the oxime bond.[40, 41] Herein, we report the utilization of the oxime click reaction for spontaneous production of high molecular weight step growth polymers. The highly efficient oxime reaction resulted in the synthesis of 35 kDa polymers within 5 minutes at 60°C and 32 kDa polymers within 13 minutes at room temperature and simply by altering the monomer ratio, polymers were synthesized with controlled end-group functionality. Finally, functional group tolerance was demonstrated by successful oxime bond formation and polymer synthesis in the presence of an acidic dialdehyde monomer, 3,5-diformylphenyl boronic acid, and a basic dialdehyde monomer, 2,2-bipyridine-4,4-dicarboxaldehyde. The rapid synthesis under extremely benign conditions demonstrates the efficiency of the oxime click reaction and indicates the potential of oxime chemistry as a versatile tool for the development of environmentally friendly step-growth polymers.

The aim of this research was to develop novel A-A/B-B step-growth polymers using highly efficient oxime click chemistry. Monomer synthesis was achieved with simple, well-known chemistry. Propane-1,3-bishydroxylamine, **M1**, was formed according to a reported literature procedure.[42] Di-benzaldehyde tetraethylene glycol, **M2**, was prepared via a carbodiimide coupling reaction between TEG and 4-formyl benzoic acid (see supporting information for characterization). The combination of bis-hydroxylamine **M1** with dialdehyde **M2** resulted in the formation of oxime linked step-growth polymers **Pa-Pc** (Scheme 1).

Scheme 1 Synthesis of Oxime Linked Polymers

Reaction Conditions	[Monomer] (mmolL-1)	Aniline (mol%)	Temperature (°C)	Reaction Time	Mn (kDa)
A	150	No catalyst	20	4 hrs	12
B	150	40	20	t < 15 min	32
C	150	40	60	t < 5 min	35

The oxime click reaction is very efficient. Without the addition of a catalyst or heat, the reaction between monomers **M1** and **M2** yielded a 12 kDa polymer after 4 hours (**Pa**, Scheme 1 Condition A). SEC analysis revealed a multi-modal trace for polymer **Pa**, indicating the formation of oligomers of various molecular weights and the potential formation of cyclic products, with the average molecular weight being 12 kDa. (Figure S1). ^{1}H-NMR analysis of the polymer product confirmed the successful formation of the oxime bond, which appears as a singlet at 8.1 ppm. The doublets at 8.03 and 7.63 ppm are attributed to the aromatic protons, while the signals at 2.15, 3.67, 3.81, 4.32 and 4.46 ppm are attributed to the methyl and ethyl groups of the polymer backbone chain (Figure 1).
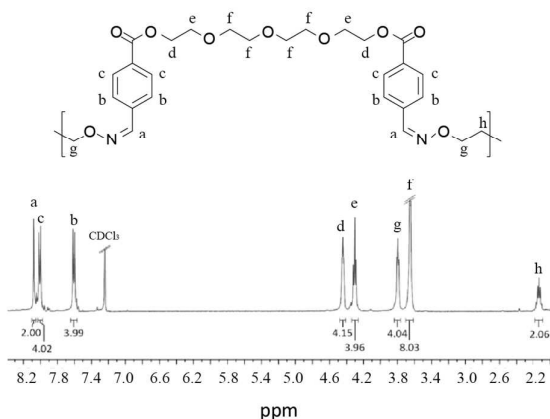

Fig. 1 ^{1}H-NMR spectra of oxime-linked polymer, **Pa**. A strong oxime singlet peak can be seen at 8.1 ppm (a) arising from the successful formation of the oxime bond.

By measuring the relative intensity of the characteristic aldehyde peak at 10.07 ppm, corresponding to the aldehyde proton on **M2**, ^{1}H-NMR offers a facile means to monitor reaction kinetics. By following the attenuation of the aldehyde peak the reaction was observed to reach complete conversion in only four hours (Figure S2). Size exclusion chromatography (SEC) confirmed that the reaction was complete after 4 hours as no further increase in polymer size was recorded (Figure S3). Therefore, SEC and ^{1}H-NMR analysis support the formation of a 12 kDa oxime-linked step growth polymer in extremely mild conditions (room temperature) and short reaction times (4 hours).

In order to synthesise high molecular weight polymers, aniline, which has been reported to significantly enhance the rate of oxime bond formation,[43] was introduced as a catalyst. Both the monomer concentration and the aniline concentration were investigated in order to optimize the synthesis to yield the highest molecular weight polymer (Table 1).

Table 1 Oxime Polymerisation Optimization

	[Monomer] (mmol/L)	Aniline (mol%)	Mn (kDa)[1]	Dispersity[1]
P1	5	20	1.5	1.5
P2	75	20	18	2.6
P3	150	20	27	2.6
P4	300	20	30	2.8
P5	150	2	20	2.7
P6	150	10	24	2.6
P7	150	20	27	2.6
P8	150	40	35	2.3

Experimental series optimizing monomer (P1-4) and aniline concentrations (P5-8) to yield the highest molecular weight polymer. All reactions were undertaken at 60°C for 6 hours. [1] Mn and dispersity calculated relative to polystyrene standards.

As the monomer concentration was increased from 5 – 300 mmolL^{-1} an increase in polymer molecular weight from 1.5 – 30 kDa was observed via SEC (Table 1. **P1-4**, Figure S4). In all cases the monomer ratios was maintained at 1:1 and were reacted in the presence of 20% aniline over 6 hours at 60°C. It can be concluded that, in general, an increase in monomer concentration results in an increase in polymer molecular weight. However, the polymer molecular weight did not increase significantly between 150 and 300 mmolL^{-1} (M_n = 27 and 30 kDa respectively). As the polymers were very similar in size, the optimum monomer concentration, which yields the highest molecular weight polymer, was determined to be 150 mmolL^{-1}

A similar set of experiments were undertaken to determine the optimum aniline concentration that yields the highest molecular weight polymer. A series of aniline concentrations, ranging from 2 – 40%, were investigated using the monomer concentration previously optimized, 150 mmolL^{-1}, at 60°C for 6 hours (Table 1. **P5-8**). SEC revealed that increasing the aniline concentration from 2 – 40% increased the polymer molecular weight from 20 – 35 kDa (Figure 2). The increase in polymer molecular weight resulting from an increase in catalyst concentration was an unexpected result as only an increase in the rate of formation, not the final molecular weight of the polymer, was expected to be effected by the catalyst concentration. However, an increase in *Mw* with catalyst concentration has been reported for other step-growth polymerizations such as the sulfate polymerization reported by Sharpless and co-workers[22] and the polycondensation of bisphenol-A bischloroformate[44] as well as various metal catalysed polymerizations.[45, 46] The optimal conditions for high *Mw* were determined to be 150 mmolL^{-1} monomer concentration and 40% aniline which yielded a 35kDa polymer after 6 hours at 60°C (Scheme 1, **Pc**).
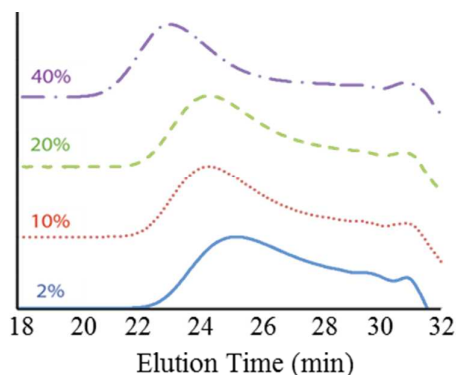
Fig. 2 SEC traces of polymers formed using an increasing concentration of aniline. P5-2% aniline (solid line), P6-10% aniline (dotted line), P7-20% aniline (dashed line), P8-40% aniline (dot-dash line). An increase in aniline concentration from 2 – 40 mol% leads to a corresponding increase in polymer molecular weight from 20 – 35 kDa (Table 1, P5-8). All reactions were undertaken over 6 hours at 60℃.

In order to determine polymer **Pc**'s acidic and hydrolytic stability SEC was utilised to measure the molecular weight under accelerated acidic and basic conditions (0.1M acetic acid or 0.1M NaOH, 50℃) for one week. SEC analysis revealed no change in molecular weight under acidic or basic conditions (Figure S5 and S6) indicating the long-term stability of the oxime polymers. Comparatively, commercially available polycaprolactone (PCL) (44 kDa) and polybisphenol A carbonate (PBA) (25 kDa) were found to degrade to 15 and 0.5 kDa respectively, after one week under basic conditions but, similar to the oxime-polymer, remained stable under acidic conditions (Figure S5 and S6). The acid sensitivity of oxime linkages is well known[28, 36, 38, 47] and the stability of **Pc** under acidic conditions indicates a potential hydrophobic shielding of the oxime bond by the neighbouring aromatic benzene ring which potentially hinders the approach of water/H_3O^+ therefore preventing oxime degradation, though further investigations are required to confirm this.

Differential scanning calorimetry (DSC) was used to analyse the thermal properties of **Pc**. The glass transition point (Tg) was found to be at 20℃ (Figure S7).

During the reaction optimization, polymerization was allowed to proceed for 6 hours. To further investigate the kinetics of the reaction SEC was utilised to monitor the polymer molecular weight every hour for 6 hours in order to determine the length of time required to achieve high molecular weight polymers. It was revealed that after one hour at 60℃ a 35kDa polymer had formed and no change in molecular weight was observed after this point (Figure S8). This indicates that the reaction is complete within one hour at 60℃. Following this, the polymerization reaction was analysed by SEC approximately 10 minutes after the initial mixing of reactants and it was revealed that a 35 kDa polymer had formed within this time period (Figure S9) indicating an extremely rapid rate of polymerization at 60℃. As the sample requires diluting by a factor of 9x for SEC analysis, the reaction is essentially stopped and any time delay incurred by the SEC machinery can be ignored.

The speed of the reaction was investigated more accurately by ^{1}H-NMR. The characteristic aldehyde and hydroxylamine peaks, at 10.07 and 11.2 ppm respectively, indicate the relative concentrations of monomers **M1** and **M2** remaining in the reaction mixture. Once the peaks are no longer visible in the ^{1}H-NMR spectrum it can be assumed that the monomer concentration is exhausted and that polymerization is near-complete. At time zero, prior to the addition of aniline, both the aldehyde and hydroxylamine peaks are clearly visible in the reaction mixture (Figure 3a). Five minutes after the addition of 40% aniline, essentially as fast as the sample can be analysed, both peaks have completely disappeared and a strong oxime peak, at 8.1 ppm, has appeared (Figure 3b). The SEC and ^{1}H-NMR analysis confirm that at 60°C (40% aniline) the reaction shows extremely high conversion to prepare a high molecular weight (35 kDa) oxime-linked step growth polymer in 5 minutes (**Pc**, Scheme 1, Condition C). Although these results demonstrate high conversions and efficiencies under already relatively benign conditions (60℃), we wanted to further establish the versatility of this chemistry under even less stringent conditions.
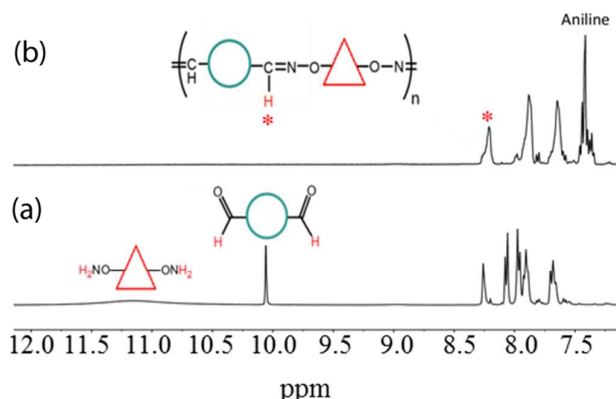
Fig. 3 (a): ^{1}H-NMR spectra of polymerization reaction mixture at 60°C recorded at time zero, before the addition of aniline. The aldehyde and hydroxylamine peaks are clearly visible. (b): ^{1}H-NMR spectra of polymer reaction at 60°C recorded 5min after the addition of 40% aniline. The rapid disappearance of both the aldehyde and hydroxylamine peaks and the appearance of a strong oxime peak at 8.1 ppm, indicate that polymerization reaction is near-complete after 5min at 60°C.

The same experiments were undertaken at room temperature in order to determine the possibility of retaining the extremely rapid rate of polymerisation and high molecular weight without heat. Approximately 10 minutes after the initial mixing of reactants at room temperature SEC analysis revealed that a 32 kDa polymer had formed (Figure S10) and no change in polymer size was observed after 10 minutes (Figure S10). Again, this demonstrates the high efficiency of oxime click chemistry and its utility to make high molecular weight polymers under extremely mild and benign conditions.

^{1}H-NMR analysis was utilised to more accurately probe the speed of the reaction. Again, the aldehyde and hydroxylamine peaks, at 10.07 and 11.2 ppm respectively, are visible prior to the addition of aniline. Compared to the polymerization at 60°C, the rate of disappearance of the aldehyde and hydroxylamine peaks at room temperature is slightly slower. ^{1}H-NMR spectra taken 3 minutes and 8 minutes after the addition of 40% aniline show a decrease in the relative intensity of the aldehyde and hydroxylamine peaks but they remain visible. Between 8 - 13 minutes after the addition of the aniline the aldehyde and hydroxylamine peaks disappeared and a strong oxime peak, at 8.1 ppm appeared (Figure S11). SEC and ^{1}H-NMR analysis confirm that a 32 kDa polymer can be formed in between 8 – 13 min at room temperature (**Pb,** Scheme 1, Condition B).

The reduction in temperature led to a small decrease in polymer size, from 36 to 32 kDa, and a slight increase in reaction time from 5 minutes to between 8 – 13 minutes. The extremely rapid formation of high molecular weight polymers under very benign conditions demonstrates the efficiency of the oxime bond formation and effectiveness of the aniline catalyst.

By using a small excess of monomer **M1** or **M2,** polymers were formed with either hydroxylamine or aldehyde functionality capping each end. The ability to control the end-group functionality of the polymer creates versatile and bio-relevant functional handles to create polymer conjugates. By using a small excess of the benzaldehyde monomer, **M2**, 1.1x that of the hydroxylamine monomer **M1**, the polymer was formed with aldehyde groups capping each end. SEC analysis of the crude reaction mixture indicated a polymer molecular weight of 28 kDa. This reduction in molecular weight is consistent with step-growth polymerization using monomer ratios other than 1:1. Through simple precipitation into water, high molecular weight polymers, terminated with aldehyde functionality, were easily isolated. The ^{1}H-NMR spectra of the polymer product, following multiple precipitations, shows a small aldehyde peak at 10.07 ppm (Figure 4). The integration of the aldehyde peak, when compared to the integration of the polymer back-bone peaks, gives a polymer molecular weight of between 30-35 kDa and indicates that the precipitations are significantly fractionating the as synthesised polymer. The molecular weight of the precipitated polymer calculated by ^{1}H-NMR agreed with the molecular weight measured by SEC, 35 kDa, (Figure S12) and confirms that the polymer is capped on both ends by the aldehyde monomer.
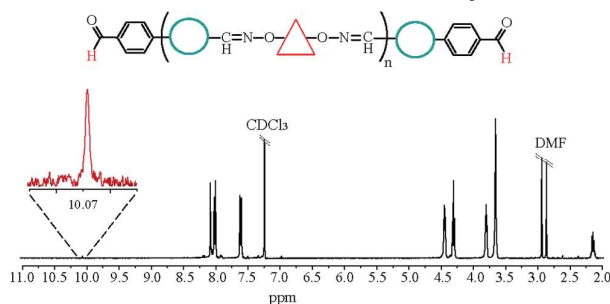
Fig. 4 ^{1}H-NMR spectra of an aldehyde-terminated polymer formed from a reaction with a 1.1 equivalent of aldehyde monomer (M2). The polymer molecular weight calculated from integration of the aldehyde peak (30 – 35kDa) agrees with the SEC analysis (37 kDa, Figure S8) confirming the formation of an aldehyde terminated polymer

The same procedure was repeated with a 1.3 equivalent of the hydroxylamine monomer, **1**. Again, the polymer molecular weight was reduced, 17 kDa (Figure S13) as expected and through precipitation the isolation of high molecular weight polymers terminated with hydroxylamine functionality were easily obtained. Following multiple precipitations, ^{1}H-NMR analysis revealed a small hydroxylamine peak and two small triplet peaks remaining, which correspond to the methyl groups of **M1** on the terminal ends of the polymer (Figure S14). The integration of these peaks was used to calculate a molecular weight of the precipitated polymer of approximately 35. The size calculated by ^{1}H-NMR agreed with the measured size determined by SEC, 30 kDa (Figure S13) and confirmed the formation of a hydroxylamine terminated polymer.

In order to demonstrate the versatility of this highly efficient chemistry we decided to make a series of functional co-polymers. Co-polymers were synthesised with an acidic dialdehyde monomer, 3,5-diformylphenyl boronic acid, and a basic dialdehyde monomer, 2,2-bipyridine-4,4-dicarboxaldehyde (Figure 5). A series of co-polymers were prepared with varying co-monomer compositions; co-polymer products being denoted **P$_{Bipy10}$**, **P$_{Bipy20}$** and **P$_{Bipy30}$** for the 10, 20 and 30 mol% 2,2-bipyridine-4,4-dicarboxaldehyde functionalised co-polymers respectively, and **P$_{Boron10}$**, **P$_{Boron20}$** and **P$_{Boron30}$** for the 3,5-diformylphenyl boronic acid functionalised co-polymers.
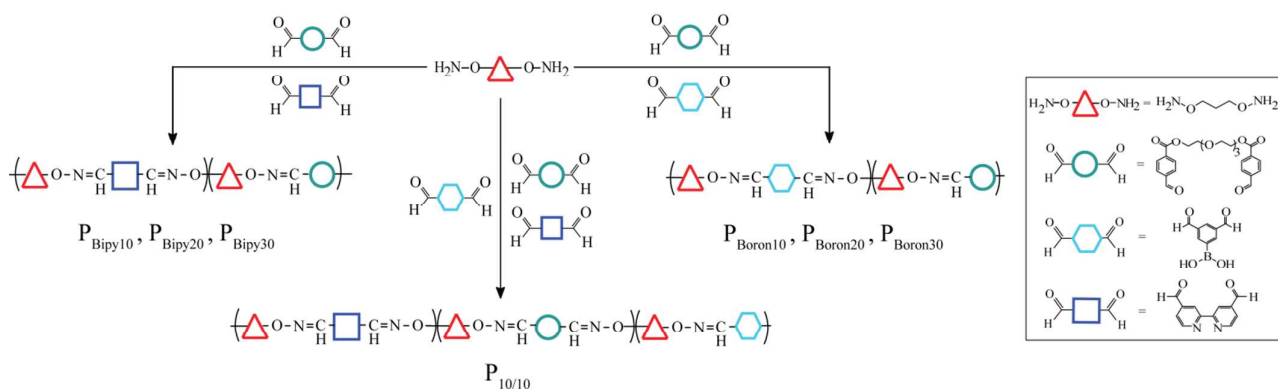

Fig 5. Synthesis of highly functionalised oxime polymers through the incorporation of 2,2-bipyridine-4,4-dicarboxaldehyde (dark blue square), 3,5-diformylphenyl boronic acid (light blue hexagon) or both. The functional group tolerance of oxime formation is demonstrated by the successful polymer synthesis in the presence of acidic and basic functionalities.

The incorporation of 10, 20 and 30 mol% of 2,2-bipyridine-4,4-dicarboxaldehyde into the oxime co-polymer (**P$_{Bipy10}$**, **P$_{Bipy20}$** and **P$_{Bipy30}$** respectively) was confirmed by ^{1}H-NMR, ^{13}C-NMR, SEC and UV-Vis spectroscopy, indicating that oxime bond formation and the subsequent co-polymer synthesis is tolerant to basic functionalities. For ease of characterisation co-polymer synthesis was undertaken with no aniline present at 60°C. ^{1}H-NMR analysis was used to confirm the incorporation of 2,2-bipyridine-4,4-dicarboxaldehyde into the co-polymer as two new doublets and a singlet appear at 8.67, 7.55 and 8.52 ppm respectively which are attributed to the aromatic protons of the bipyridine ring and a new peak at 8.14 ppm appears which is attributed to the bipyridine oxime proton (Figure 6, peaks a, b, c and d respectively, Figure S15). The relative percentage of 2,2-bipyridine-4,4-dicarboxaldehyde was increased from 10 to 20 to 30 mol% and the complete integration of the higher ratios of

co-monomer was confirmed by ^{1}H-NMR (Figure S15). The integration of the characteristic bipyridine peaks increased from 0.2 to 0.4 to 0.6 as the 2,2-bipyridine-4,4-dicarboxaldehyde ratio was increased from 10 to 20 to 30 mol% (Figure 6 boxed insert, peaks a, b, c and d) and indicates 100% incorporation of the 2,2-bipyridine-4,4-dicarboxaldehyde co-monomer. Due to the extremely high efficiency of oxime formation, precise control over the degree of incorporation of functional co-monomers into the co-polymer can be achieved stoichiometrically.
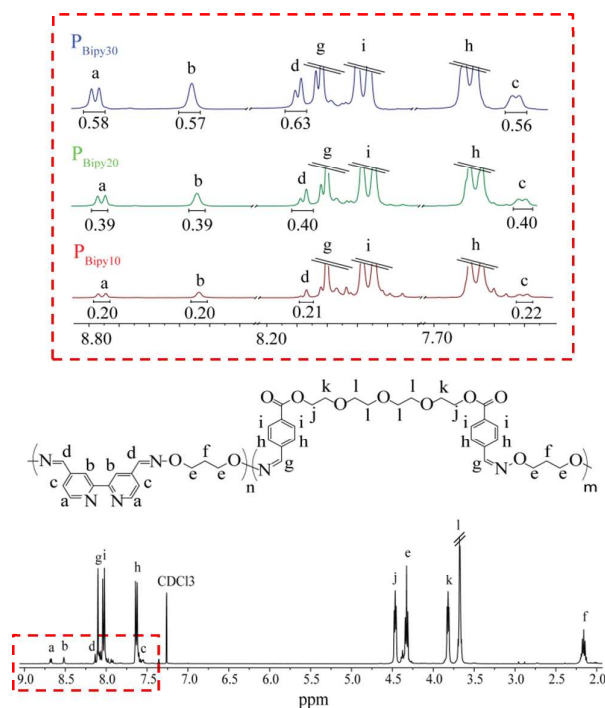

Fig. 6 ^{1}H-NMR spectra of P_{Bipy10}. New peaks attributed to the bipyridine group; a, b, c and d can be seen at 8.67, 8.52, 8.14 and 7.55 ppm respectively. Boxed insert shows the increase in intensity of peaks a, b, c and d as the bipyridine incorporation is increased from P_{Bipy10} to P_{Bipy20} and P_{Bipy30}.

Further confirmation was performed using ^{13}C-NMR. Analysis of P_{Bipy30} indicates the successful incorporation of the 2,2-bipyridine-4,4-dicarboxaldehyde co-monomer into the polymer as new peaks at 149.6, 145.6, 141.1, 120.8 and 119.3 ppm appear which are attributed to the carbons in the bipyridine ring and a new peak at 156.3 ppm appears which is attributed to the oxime carbon. (Figure S16).

Visually, the oxime polymers turn from colourless to a purple colour upon 2,2-bipyridine-4,4-dicarboxaldehyde incorporation. The colour change was observed by UV-Vis spectroscopy where a new absorbance peak at 330nm was detected which was attributed to absorbance by the bipyridine. The absorbance band increases in intensity going from P_{Bipy10} to P_{Bipy20} and to P_{Bipy30} further confirming the increase of co-monomer incorporation (Figure S17).

Finally, SEC was utilised to determine whether the bipyridine incorporation had any effect on the molecular weight of the co-polymers. Surprisingly, the addition of 10 mol% bipyridine (P_{Bipy10}) increased the co-polymer molecular weight from 12 kDa for the uncatalysed polymerisation (**Pa**) to 34 kDa (Figure S18). A further increase in bipyridine mol% increased the co-polymer molecular weight to above that of the original aniline catalysed polymer, **P8** (35 kDa) to 55 kDa for P_{Bipy20} and 106 kDa for P_{Bipy30} (Figure S18). It is interesting to observe the increase in co-polymer molecular weight as the bipyridine incorporation is increased which is believed to be attributed to the more electron deficient dialdehyde. The electron withdrawing bipyridine ring increases the partial positive charge on the carbonyl carbon making the nucleophilic attack by the hydroxylamine nitrogen more favourable. The increase in the rate of oxime and hydrazone formation due to increasing the electron withdrawing substituents of the reacting aldehydes and ketones has been reported before[48, 49] and allows for the synthesis of high molecular weight polymers without the aniline catalyst.

The functional group tolerance was demonstrated further by the successful incorporation of 3,5-diformylphenyl boronic acid into the oxime co-polymer at 10, 20 and 30 mol% (**P_Boron10**, **P_Boron20** and **P_Boron30** respectively) which was confirmed through ^{1}H-NMR, ^{13}C-NMR and SEC analysis and indicates that oxime formation and subsequent polymer synthesis is tolerant to acidic functionalities. The ^{1}H-NMR analysis of **P_Boron10**, **P_Boron20** and **P_Boron30** reveals clear differences in the shape and integration of the peaks in the aromatic region when compared to the un-functionalized polymer, indicating the overlap of proton signals and the incorporation of phenyl boronic acid (Figure S19). To confirm the phenyl boronic acid incorporation, **P_Boron30** was analysed by ^{13}C-NMR which revealed new peaks at 145, 134.2 and 132.2 ppm which are attributed to the aromatic ring carbons of phenyl boronic acid and a new peak at 148.5 ppm which is attributed to the new oxime carbon (Figure S20). The ^{13}C signal for the *ipso*-position carbon, the carbon attached to the boronic acid, could not be identified in CDCl$_3$ due to the line broadening resulting from the short relaxation time of boron, which has been previously reported.[50]

SEC was used to calculate the molecular weight of **P_Boron10**, **P_Boron20** and **P_Boron30** which were found to be 26, 20 and 18 kDa respectively (Figure S21). It can be seen that at low phenyl boronic acid ratios there is an increase in co-polymer molecular weight when compared to **Pa** (12 kDa)**.** However, increasing the boronic acid ratio decreases co-polymer molecular weight.
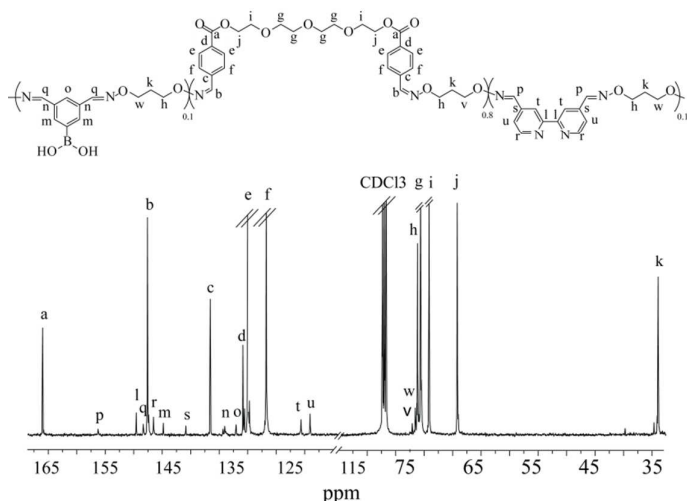

Fig. 7 ^{13}C-NMR spectra of **P_10/10**. Identification of characteristic peaks attributed to both the bipyridine and phenyl boronic acid indicate the successful incorporation of both functionalities.

The power of this reaction was further demonstrated by the formation of oxime co-polymers in the presence of both acidic and basic co-monomers. The highly functional co-polymer product, denoted **P_10/10**, was synthesised in the presence of 10 mol% 3,5-diformylphenyl boronic acid and 10 mol% bipyridine-4,4-dicarboxaldehyde with successful incorporation of both functional co-monomers being confirmed by ^{1}H-NMR (Figure S22) and ^{13}C-NMR analysis (Figure 7). The characteristic bipyridine peaks are easily identifiable in the ^{1}H-NMR spectra (Figure S22, peaks l, m, n and o) as is the splitting of the aromatic peaks (Figure S22, peaks f, g and h) by the phenyl boronic acid. The ^{13}C-NMR clearly demonstrates the phenyl boronic acid incorporation (Figure 7, peaks m, n, o and q) and the bipyridine peaks (Figure 7, peaks l, p, r, s, t and u), indicates the successful formation of the highly functionalised polymer, **P_10/10**. SEC was used to calculate the molecular weight of **P_10/10** which was found to be 28 kDa (Figure S23), which lies in-between **P_Boron10** (26 kDa) and **P_Bipy10** (34 kDa). The demonstrated functional group tolerance of oxime-based polymers confirms the high selectivity and orthogonality of oxime formation and the possibility of oxime step-growth polymer synthesis in the presence of various functional groups. The high efficiency of oxime bond formation allowed for 100% incorporation of different, functional monomers and gives total control over the degree of polymer-functionalization through simple, stoichiometric control. The incorporation of multiple, chemically-distinct monomers allows for the facile synthesis of highly functionalised polymeric materials possessing many different chemical moieties for further post-modifications.

Conclusions

The oxime click reaction is an extremely rapid and versatile chemistry to prepare high molecular weight step-growth polymers. The ideal monomer and catalyst concentrations were identified, 150 mmolL^{-1} and 40 mol% respectively, these conditions resulted in the synthesis of 35 kDa polymers in 5 minutes at 60℃ and 32 kDa polymers in under 13 minutes at room temperature. To the best of our knowledge these are some of the fastest step-growth polymerization conditions ever reported. Furthermore, by using a small excess of either the aldehyde or hydroxylamine monomer, polymers were formed with hydroxylamine or aldehyde functionalities capping each end. The functional group tolerance of the new oxime-based materials was demonstrated by successful synthesis in the presence of an acidic and a basic dialdehyde indicating the potential for the facile production of highly functionalised polymeric materials. We believe that these results indicate the great potential of oxime click chemistry as a new means for the synthesis of complex, high molecular weight step-growth polymers under extremely benign conditions.

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GRAPHICAL ABSTRACT FIGURE

High Molecular Weight
Benign Reaction Conditions

Functional Group Tolerance