



HAL
open science

How to modulate chemical structure of polyoxazolines by appropriate functionalization

Brieuc Guillerm, Sophie Monge, Vincent Lapinte, Jean-Jacques Robin

► **To cite this version:**

Brieuc Guillerm, Sophie Monge, Vincent Lapinte, Jean-Jacques Robin. How to modulate chemical structure of polyoxazolines by appropriate functionalization. *Macromolecular Rapid Communications*, 2012, 33 (19), pp.1600-1612. 10.1002/marc.201200266 . hal-00739811

HAL Id: hal-00739811

<https://hal.science/hal-00739811>

Submitted on 9 Oct 2012

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

How to modulate chemical structure of polyoxazolines by appropriate functionalization

Brieuc Guillerm, Sophie Monge, Vincent Lapinte,* Jean-Jacques Robin

Institut Charles Gerhardt Montpellier UMR5253 CNRS-UM2-ENSCM-UM1 - Equipe Ingénierie
et Architectures Macromoléculaires, Université Montpellier II – Bat 17 – cc1702, Place Eugène
Bataillon 34095 Montpellier Cedex 5

Corresponding author: Vincent.Lapinte@univ-montp2.fr; Tel: 33-4-67-14-48-32; fax: 33-4-67-
14-40-28.

Abstract

Polyoxazolines (POx) are increasingly studied as polymeric building blocks due to the possibility of affording tunable properties. Additionally, as it was proved that biocompatibility and stealth behavior of POx are similar to that of poly(ethylene glycol) (PEG), it became challenging to develop polyoxazoline-based (co)polymers. Even if POx have a lot of advantages, they also show an important drawback as it is to date impossible to prepare high molecular weight polyoxazolines, with low polydispersity indexes. So, it appears important to judiciously functionalize them. This review covers the multiple ways of functionalization of polyoxazolines. The use of functional initiators, functional terminating agents, and 2-R-2-oxazolines with R functional side group is detailed. In conclusion, some perspectives on POxfunctionalizations are also reported, with functions permitting selective “click” reactions.

Keywords: cationic polymerization; functionalization of polymers; oligomers; ring-opening polymerization

1. Introduction

Polyoxazolines (POx) represents nowadays a valuable type of macromolecules for many reasons. For instance, they are considered as bio-inspired polymers as they are structural isomers of both polyacrylamides, with a pendant amide function, and polypeptides, bearing amide function in the main chain.^[1] To date, they were mainly investigated toward biomedical applications^[2, 3] due to their biocompatibility, biodistribution, blood clearance and protein adsorption.^[4-8] Based on their low toxicity, poly(2-oxazolines) are anticipated to be suitable to build antimicrobial materials, when associated with quaternary ammonium salts. They are also employed as drug carriers, for instance. For all these reasons, POx are considered as similar to poly(ethylene glycol) (PEG). It is also important to notice that the latter showed important drawbacks.^[9, 10] Indeed, it was notably shown that PEG leads to adverse side effects in the body, caused by the polymer itself or by side products which are toxic. Unexpected pharmacokinetic behavior can also occur with PEG-based carriers. These non negligible problems led to the development of polyoxazoline derivatives which are today considered as available alternative to PEG. Other important characteristic of POx-based materials is their thermosensitivity as some of them have a lower critical solution temperature (LCST), depending on the R group of the pendant chain.^[11] Thermoresponsiveness is often used to build drug carriers,^[12] and until now the most studied thermosensitive polymer in the literature is poly(N-isopropylacrylamide) (PNiPAM) as its LCST (around 32 °C) is relatively independent of environmental conditions. As PNiPAM is not proved to be biocompatible, POx may replace it and, additionally, the LCST value of such polymers can be modulated from 5 to 90 °C as a function of the R group of the pendant chain, which is a great advantage.

Well-defined POxs are easily prepared by cationic ring-opening polymerization (CROP) of cyclic 2-R-2-oxazolines and various properties are obtained as a function of the nature of the R pendant

alkyl chain (Me, Et, Pr, *etc.*). Several teams demonstrated the effect of the R side group on the properties in solution such as solubility in the common solvents and/or water, and the presence of a lower critical solution temperature (LCST). The influence of the R groups was also examined in solid state with the determination of mechanical^[13, 14] and thermal^[15-18] properties. Whereas POx are very promising materials, one of their drawbacks appears to be very restrictive. Indeed, whatever the nature of 2-oxazoline monomer and the initiator, the molecular weight of well-defined POx with low polydispersity index, usable for smart applications, is only limited to about 40 kg.mol⁻¹ (Table 1). Low molecular weight is an important limitation for the spread development of polyoxazolines in comparison with poly(ethylene glycol) (PEG) competitor (notably in terms of biocompatibility and stealth behavior) which can be prepared with very high molar masses. For this reason, functionalization appears to be the key parameter to overcome this problem. One of the benefits of POx is the possible functionalization of the lateral chain, which is impossible in the case of PEG. Additionally, POx has also the great advantage of being easily converted to polyamines by treatment in acidic medium. In the case of 2-oxazoline bearing alkyl chains, no relation between the nature of the side group and the maximum molecular weight was found. A lot of studies mention transfer reactions as explanation of limited molecular weight but only a few of them investigate in detail this side reaction. Lévy and Litt^[19] as well as Kourti,^[20] in the particular case of initiator based on metallocene, proposed a monomer transfer reaction based on the abstraction of the α -proton of monomer and its transfer on the terminal oxazolinium species of the propagating polymer chain. Schubert et al. illustrated the transfer reaction in the case of 2-ethyl-2-oxazoline using matrix assisted laser desorption/ionization-time of flight (MALDI-Tof) experiments.^[21]

INSERT TABLE 1

In order to increase the molecular weight and decrease the reaction time, the polymerization of various 2-R-2-oxazolines was achieved by Schubert *et al.*^[22, 23] using microwaves. The latter, combined with an increase of the reaction temperature, allowed decreasing the reaction time but did not lead to higher molecular weights.^[24] Indeed, the synthesis of longer well-defined polymer chains in a living way fails as the average molecular weight distributions broaden for polymerization degrees higher than 300. As a consequence, to extend the properties of low molecular weight polyoxazolines, the only solution is to functionalize them with appropriate reactive groups in order to further extend their molar mass by combination with other polymers^[25] or to add specific molecules to change some of their properties. For instance, it was proved that antimicrobial activity and hemocompatibility of telechelic poly(2-methyloxazoline) is greatly influenced by the nature of the end groups.^[26]

Functionalization of the POx chains is obtained by using functional initiators^[27] or terminating agents^[28] or via the use of 2-R-2-oxazolines where R represents a functional pendant group^[29] (Figure 1). It is also important to notice that functional groups of initiator or monomer interfere in some cases with the cationic ring-opening polymerization of 2-R-2-oxazoline.^[30] This usually detrimentally affects yields and the control of molecular weight and such problems are minimized by using appropriate protecting groups on initiator (P' for protecting group in Figure 1), terminating agent or R pendant group (P for protecting group in Figure 1). This protection strategy notably reduces or removes the nucleophilicity and basicity of the reactive sites by steric hindrance and / or electronic effects. Indeed, the cationic character of the polymerization process is

influenced by all nucleophilic reagents in the reaction medium coming from impurities like water, by-product of the initiator or competing nucleophilic site.

INSERT FIGURE 1

To develop smart applications, it is important to prepare well-defined polyoxazolines with controlled functionality and molecular weight, and the appropriate functional groups at the chain ends or along the backbone.^[31] In this review, we describe functionalized polyoxazolines suitable for the preparation of well-defined polyoxazoline-based (co)polymers. Functionalized polyoxazolines can be obtained using appropriate functional initiators, terminating agents and pendant chains of 2-R-2-oxazolines. These different molecules are listed and the choice in the functional groups is discussed knowing that some protecting groups are able to push back the limits of incompatibility between functional reactants and CROP process. The functionalization reactions are essential as it will allow the development of innovative materials based on polyoxazolines. Even if lots of examples are reported in the literature, some interesting perspectives can also be envisaged and will be discussed at the end of this contribution.

2. Initiator-based functionalization

To date, the cationic ring-opening polymerization of 2-oxazolines has been accomplished using many initiators including Lewis acids such as boron trifluoride ($\text{BF}_3\text{-OEt}_2$) (IIIa column of periodic table, Figure

2)^[32]zirconium/tris(pentafluorophenyl)borate,^[20]trihalogenobismuthine,^[33]and alkyl esters such as tosylates, triflates (VIa column of periodic table, Figure 2) and halides (VIIa column of periodic table, Figure 2). The alkyl halide initiators range from chloride,^[34] bromide^[35] to iodide^[36, 37] as well as acetyl halide.^[38] The alkyl iodide initiators are mostly converted *in situ* from chloride^[39, 40] or bromide^[41] analogues using NaI or KI reactants. The simplest iodine initiator is the molecular iodine for which the mechanism of polymerization has recently been elucidated.^[42] Aoi et al. have extensively studied the influence of the nature of the initiator on the mechanism of polymerization which can be ionic and/or covalent. Chemical structure of the initiator also influences the control of the molecular weight. Indeed it was shown that a lack of control with the persistence of residual initiator until the end of the polymerization as well as sometimes a latency period at the beginning of the polymerization is observed with some of the initiators, as demonstrated in the case of 4-(*p*-toluenesulfonate)methyl-1,3-dioxolan-2-one,^[43] 3-butynyl tosylate,^[34] tosylate and triflate initiators based on sugar,^[44] and macroinitiators such as α -methoxy- ω -4-toluene-sulfonate poly(ethylene oxide).^[45] An alternative approach to overcome a slow initiation consists in preparing first the propagating species composed of the initiator after reaction with one oxazoline monomer unit. It was widely shown that this oxazolinium compound favors the control of the polymerization related to the precursor initiator.^[46] α -Functionalized POx were also developed. Either the functional group carried by the initiator does not react during the polymerization or it provokes transfer reactions. In the latter case, a protecting step is first required.^[30]

INSERT FIGURE 2

The cationic ring-opening polymerization process is compatible with a lot of functions based on atoms of IVa column of the periodic table including carbon and silicon (Figure 2). The most studied initiators have got alkyl chains of various lengths^[22, 36, 37, 47-49] as well as perfluorinated chains.^[28, 50] The compatibility also exists with unsaturated aliphatic initiators with double^[51-53] or triple bonds^[34, 54, 55] even if transfer reactions appeared above 50% conversion in the latter case. These unsaturated groups have an interest because they can be involved in two types of “click” reaction: thiol-ene coupling (TEC) and copper catalyzed azide-alkyne cycloaddition (CuAAC) named Huisgen’s cycloaddition. These reactions allow the modification of polyoxazoline chain ends^[1] and the synthesis of amphiphilic block copolymers by polymer-polymer coupling.^[54] Initiators bearing acetal, oxirane,^[56] cyclocarbonate,^[43] ester^[41, 57] and silane^[58, 59] derivatives also lead to the CROP of oxazolines without any side reactions (Figure 3). Macroinitiators deriving from cholesterol^[56] and vegetable oils as castor oil,^[57] diacylglycerol,^[56] 1,2-*o*-dioctadecyl-*sn*-glyceryl^[48] are employed in the synthesis of amphiphilic copolymers. The CROP of 2-oxazoline is also compatible with bis-initiators bearing unsaturations like acetylenic groups^[55, 60] and double bonds.^[52, 61, 62] Multi-functional initiators based on alkyl chains,^[61, 63, 64] aromatic rings with two reactive sites in ortho, meta or para positions^[52] or six reactive sites^[65] are used in the elaboration of more complex structures. Other multi-initiators are described such as tetrachloro or iodo initiators from porphyrine.^[66]

INSERT FIGURE 3

Otherwise, some functional initiators need the protection of their competitive reactive sites such as alcohol, thiol, or amine groups (Figure 4) which can interfere during the CROP process. These functions are based on heteroatoms belonging to Va and VIa columns of the periodic table (Figure 2). In initiator structure, the amine function is converted into urethane,^[49] quaternary ammonium salt^[26] whereas thiol is transformed into thioether. Alcohol groups are converted into ester groups including adamantyl which leads to supramolecular network by interactions,^[67] or into acetal or cyclocarbonate groups. Another protecting group of alcohol function is the silyl ethers like the *tert*-butyldiphenylsilyl ether.^[30] Alcohol groups are also protected into acetate groups in the synthesis of glyco-initiator.^[44] Finally, some initiators bear polymerizable groups such as vinyl^[68] and styrenic^[69] groups in order to further elaborate graft copolymers.

INSERT FIGURE 4

3. Terminating agent-based functionalization

The cationic nature of the oxazoline polymerization and the persistence of the oxazolinium propagating species in terminal position of the polymer chain require a nucleophilic reagent as terminating agent to stop the propagation. Several reactants based on sulfur, oxygen and nitrogen chemistries were already described as illustrated in Figure 5. The terminating agents belong to Va and VIa columns of the periodic table (Figure 2). The most widely used terminating agent is water^[47, 70, 71] or above all its activated corresponding ion: hydroxyl ion in methanolic sodium hydroxide solution^[72] or sodium hydrogen carbonate.^[73] In this particular case, whatever the activated species, a hydroxy-terminated polyoxazoline is obtained but the

mechanism of the terminating stage is not the same. Indeed, in the presence of sodium hydrogen carbonate, attack on the 2-position of the oxazolinium ring occurs while attack of nucleophilic reagent takes place on the 5-position of the oxazolinium specie.^[74] The other main family deals with amines which have an adequate nucleophilic character ($pK_a > 10$) to react with oxazolinium species. The basic nitrogen derivative, ammonia, is successfully used as terminating agent^[75] while the primary amines are the most important group, ranging from aliphatic compounds with long chain to obtain amphiphilic copolymers,^[76] aniline^[51] to various functional primary amines.^[69, 77] Secondary cyclic amines as terminating agents are represented by piperidine,^[78] piperazine derivatives^[39, 79] or morpholine^[80] and by bis-functional acyclic amines.^[81, 82] Even if the tertiary amines such as pyridine,^[56] pyrrole^[35] and linear amine with long alkyl chain are less reactive than those less substituted, they react as terminating agents for biocide applications.^[83] An interesting nitrogen terminating agent is sodium azide (NaN_3) which further leads to Huisgen's cycloaddition to generate amphiphilic copolymers by click reaction.^[63, 84] Another approach consists in the use of bis-terminating agent like ethylenediamine in excess to avoid the coupling between two polyoxazoline chains.^[26] Functional amine with alcohol group in ω -position is also employed to obtain hydroxy-terminal polyoxazoline without using potassium hydroxide, preventing from the hydrolysis of the ester group of the initiator structure.^[67] Another class of terminating agents is based on sulfur derivatives like sodium thiolates,^[85-88] notably allowing the introduction of carboxylic acids,^[88] for instance, or on carboxylic acids and corresponding carboxylate salts such as acrylic acid,^[87, 89] methacrylic acid,^[90-92] maleic acid,^[93] glutaric acid,^[94] cinnamic acid^[95] and terephthalic acid.^[90]

As explained in the case of functional initiators, functional terminating agents are employed to transform polyoxazolines in macromonomers for the further elaboration of grafted copolymers.

The polyoxazolinemacromonomers belong to styrenic,^[39, 96] acrylate^[89, 97] and methacrylate families.^[77, 91, 92] The last class of terminating agents gathers difunctional reagents which permit the increase of the polyoxazolinemolecular weight by a double reaction with central unsaturation coming from the agent.^[90, 93, 94]

INSERT FIGURE 5

4. Functionalized monomers

The third method of polyoxazolinefunctionalization corresponds to the use of 2-R-2-oxazoline monomer bearing R functional pendant group (Figure 6). This possibility of functionalization is a major benefit related to poly(ethylene glycol) and offers a supplementary scope of properties in comparison with the latter. In this purpose, Hoogenboom *et al.* investigated the feasibility of the preparation of various 2-substituted 2-oxazolines as well as their polymerization.^[98] Whatever the R group, the side chain of the monomer may not react during the CROP process. Consequently, a protecting group has to be used when necessary to avoid any side-reaction of R group with the propagating species. The R pendant groups based on carbon and silicon (IVa column of periodic table, Figure 2) do not require masking groups. A lot of 2-oxazolines bearing hydrocarbonated pendant groups were developed while few 2-oxazolines with silane pendant chains were synthesized.^[99, 100] The most studied 2-oxazoline monomers bear linear alkyl chain with various lengths ranging from methyl to undecyl groups.^[19, 71, 75, 99, 101-105] Additionally, the alkyl chain can also be substituted, with *iso*-propyl,^[75] *iso*-butyl,^[103] *ter*-butyl,^[106] neopentyl,^[107] ethylheptyl^[102] and ethylpentyl groups.^[108] The influence of R alkyl group on the polymer solubility,

mechanical (Young modulus) and thermal properties (glass transition temperature value) properties of the final material has widely been described in the literature. Poly(2-methyl-2-oxazoline) and poly(2-ethyl-2-oxazoline) are hydrophilic^[16] whereas longer R groups or aromatic group lead to hydrophobic character,^[107] reflecting the importance of R pendant chain on the solubility. Glass transition temperatures range from 15 to 105°C as a function of the R chain length.^[15-18] Otherwise, the Young modulus is only influenced by R groups containing less than four carbons.^[13, 14] The impact of the alkyl chain on the behavior of polyoxazoline in solution is also illustrated by the existence of a LCST between 5 and 90 °C^[15, 18, 109] which is observed for most POx, except for 2-methyl-2-oxazoline.

2-Oxazoline monomers bearing unsaturation are described with single (internal or terminal)^[98, 103, 110] or several double bonds such as 2-isopropenyl-2-oxazoline^[92] which polymerizes under free,^[111] controlled (RAFT) radical processes,^[112] anionic and cationic polymerizations.^[113] 2-(9-Decenyl)-2-oxazoline was modified by thiol-ene coupling in the presence of 2-mercaptoethanol giving polyols for polyurethane formulations.^[110] The unsaturations of soy-based 2-oxazoline monomer were employed to crosslink the core of micelles under UV-irradiation.^[114, 115] The same strategy is used with tetrathiol in order to elaborate novel photoresist.^[116] Alkyne-based oxazolines with one or two unsaturations are also described and employed for Huisgen's CuAAC cycloaddition.^[79] For instance, Schlaad *et al.* investigated the crosslinking of block copolymer micelles by thiol-yne reaction.^[117] Several 2-oxazolines bearing cycloaliphatic R side chains were described with strained cycle,^[118] bicycle or tricycle.^[98] 2-Oxazolines with aromatic R side groups were also synthesized^[19] with various substituents^[29, 98, 105, 119] including perfluorogroup.^[103, 120] Other aromatic systems were investigated with furanyl^[103, 121] and carbazolyl cycles.

As illustrated in Figure 2, the mono-halogenated derivatives based on the elements of the VIIa column of the periodic table cannot be considered as pendant chain due to their high reactivity as initiator which can make them react, thus building branched polyoxazolines. Moreover no protecting group exists with easy deprotection protocol for such compounds. From the Va column, only few examples of pendant chain bearing nitrogen or phosphorus atoms are detailed in the literature because of their high reactivity requiring a protecting step with *tert*-butyloxycarbonyl (Boc) group^[98, 119] and into phosphoric ester, respectively.^[98] Several examples of pendant chains bearing nitrogenated cycle are described with azetidiny, azepanyl, piperidine, 1-azocanyl, 1-morpholine, 1-pyrrolidinyl^[122] and pyrrolidonylethyl.^[123] After the hydrocarbonated R side groups, the oxygenated ones are the most numerous examples in the literature whereas those based on sulfur are rare^[103] (VIa column of periodic table, Figure 2). Alcohol end group^[104] on the pendant chain was investigated even if a protecting group was usually used such as ester^[104] or acetal group,^[98, 123] sometimes cyclic.^[124] An interesting example is the glycooxazoline on which each alcohol group is protected into acetate groups. The last class of R side groups in 2-oxazoline is represented by polymer chains like polystyrene,^[15-17] poly(ethylene oxide)^[123] and poly(ϵ -caprolactone).^[125] These 2-oxazolines are employed as macromonomers in the synthesis of graft copolymers.

INSERT FIGURE 6

5. Conclusion and Perspectives

In this review, we described the different ways of functionalization of polyoxazolines using appropriate initiator, terminating agent or *via* the R group of the pendant chain of the 2-R-2 oxazoline monomer. It was shown that initiators can bear polyhedral oligomeric silsesquioxane, saccharide, steroid, vegetable oil derivatives, for instance. Terminating agents can notably allow the introduction of a polymerizable groups or sol-gel precursors at the chain end. The wide number of functionalizations of polyoxazolines also comes from R functional pendant groups in the 2-R-2-oxazoline monomers notably with glucose units, aromatic or fluorescent groups. All these possibilities permit the easy synthesis of very different polyoxazolines with lots of different properties which can be adapted to the targeted application, often in the biomedical field due to the biocompatibility and stealth behavior of POx. Easy functionalization explains the interest brought to polyoxazolines by the researchers who noticed a great contribution of these materials compared to poly(ethylene glycol) which proved these last years to generate some problems for biomedical applications as explained in the introduction of this review. Additionally, in the case of PEG, functional groups cannot be introduced so easily. On the reverse, functionalizations of POx lead to further reactivity and permit the building of more complex macromolecular architectures by polymer-polymer coupling or by using polyoxazoline derivatives as macroinitiators.

Among all possibilities of functionalization of POx, selective and orthogonal reactions named “click” reactions appear to be of interest and were already successfully employed in macromolecular chemistry.^[126] More precisely, POx functionalizations have already been described in the literature using thiol-ene^[127] and thiol-yne^[117] reactions, and the Huisgen’s cycloaddition catalyzed by copper (CuAAC) reaction.^[79, 128] In such cases, polyoxazolines bear double, triple bonds, or azido groups (Figure 7).

INSERT FIGURE 7

Another example involving POx deals with a multifunctional copoly(2-oxazoline) containing α -anthracene and ω -azide termini as well as pendant alkene group in the side chain (Figure 8).^[128] In that case, three different “click” reactions are achieved: (i) azide-alkyne cycloaddition, (ii) Diels-Alder reaction, and finally (iii) thiol-ene reaction. This example is very interesting as it shows that multi functional polyoxazolines can be prepared leading to complex chemical structures with a very good control over the molecular weight of the polymer.

INSERT FIGURE 8

From works already described in the literature, some perspectives for the development of new functionalized polyoxazolines can be considered, based on “click” reactions (Figure 9). Indeed, from multi-functional POx just described, it is obvious that Diels-Alder “click” must be studied, taking into account previous work reported by Saegusa^[129] and Stevens.^[130] The great interest of the Diels-Alder reaction is that it is reversible as a function of the temperature. So, thermoreversible Diels-Alder reaction could lead to the release of polyoxazoline bearing unsaturation in terminal or pendant groups.^[131] Thus, new polyoxazolines bearing diene have to be prepared to react with a dienophile. On the other hand, POx dienophile has already been synthesized and could react with diene. Another possibility consists in developing “pentafluoro” clicking, as already mentioned in the literature for other kinds of polymers.^[132] This reaction

corresponds to the “clicking” of thiol with pentafluoro groups, the latter being introduced via the initiator of in the pendant chain of the oxazoline monomer (Figure 9).

INSERT FIGURE 9

These perspectives demonstrate that the synthesis of various polyoxazoline-based (co)polymers is still possible, by using already prepared polyoxazolines or new ones with useful functionalities. These new structures might lead to innovative materials that could be employed for smart applications, notably for the biomedical field which requires a good control over the molar mass and the molecular weight distribution, and also appropriate functionalities.

Figure Captions

Table 1. Limited molecular weights of polymer chains for various oxazoline monomers allowing the obtaining of well-defined polyoxazolines with low polydispersity indexes.

Figure 1. General synthetic considerations for the synthesis of functionalized polyoxazolines (Ini: initiator, T: terminating agent, P and P': protecting groups).

Figure 2. The terminating agents and the pendant chains of oxazolines bearing various elements of the periodic table as well as the nature of the initiators.

Figure 3. Functionalized initiators for the cationic ring-opening polymerization of 2-R-2-oxazolines.

Figure 4. Initiators bearing additional protected and unprotected groups.

Figure 5. Terminating agents for the cationic ring-opening polymerization of 2-R-2-oxazolines.

Figure 6. R side groups of 2-R-2-oxazoline allowing the functionalization of POx pendant chains.

Figure 7. Polyoxazolines bearing functional groups allowing “click chemistry” reactions (All chemical structures were employed in “click” reactions except azido-containing polyoxazoline with aromatic ring, as mentioned).

Figure 8. Chemical structure of multi-functionalized poly(2-oxazoline) allowing the incorporation of residues by three orthogonal “click” reactions (Diels-Alder, thiol-ene reactions, and azide-alkyne cycloaddition.^[128]

Figure 9. Perspectives concerning the synthesis of functionalized polyoxazolines from precursors bearing appropriate functionality.

Table 1. Limited molecular weights of polymer chains for various oxazoline monomers allowing the obtaining of well-defined polyoxazolines with low polydispersity indexes.

R	DP_{n,exp}	M_{n,max} (g.mol⁻¹)	<i>D</i>
Me ^[83]	149	13000	1.04
Et ^[38, 133]	404	40000	1.20
Pr ^[134]	106	12000	1.04
<i>i</i>Pr ^[75]	86	10000	1.02
Bu		13000	
Pent		14000	
Hex	100 ^[14]	15000	1.20
Hept		17000	
Non		20000	
Ph ^[73]	51	8000	1.31

D: polydispersity index.

Figure 1. General synthetic considerations for the synthesis of functionalized polyoxazolines (Ini: initiator, T: terminating agent, P and P': protecting groups).

IIIa	IVa	Va	VIa	VIIa
B	C	N	O	F
Al	Si	P	S	Cl
				Br
				I

..... : terminating agent
 — : initiator
 ■ : R pendant chain

Figure 2. The terminating agents and the pendant chains of oxazolines bearing various elements of the periodic table as well as the nature of the initiators.

Figure 3. Functionalized initiators for the cationic ring-opening polymerization of 2-R-2-oxazolines.

Figure 4. Initiators bearing additional protected and unprotected groups.



Figure 5. Terminating agents for the cationic ring-opening polymerization of 2-R-2-oxazolines.

Figure 6. R sidegroups of 2-R-2-oxazoline allowing the functionalization of POx pendant chains.

Figure 7. Polyoxazolines bearing functional groups allowing “click chemistry” reactions (All chemical structures were employed in “click” reactions except azido-containing polyoxazoline with aromatic ring, as mentioned).

Figure 8.Chemical structure of multi-functionalized poly(2-oxazoline) allowing the incorporation of residues by three orthogonal “click” reactions (Diels-Alder, thiol-ene reactions, and azide-alkyne cycloaddition).^[128]



Figure 9. Perspectives concerning the synthesis of functionalized polyoxazolines from precursors bearing appropriate functionality.

References

- [1] H. Schlaad, C. Diehl, A. Gress, M. Meyer, A. L. Demirel, Y. Nur, A. Bertin, *Macromolecular Rapid Communications***2010**, *31*, 511.
- [2] R. Hoogenboom, *Angewandte Chemie International Edition***2009**, *48*, 7978.
- [3] R. Hoogenboom, H. Schlaad, *Polymers***2011**, *3*, 467.
- [4] M. Bauer, C. Lautenschlaeger, K. Kempe, L. Tauhardt, U. S. Schubert, F. D., *Macromolecular Bioscience***2012**. (doi: 10.1002/mabi.201200026)
- [5] F. C. Gaertner, R. Luxenhofer, B. Blechert, R. Jordan, M. Essler, *Journal of Controlled Release***2007**, *119*, 291.
- [6] P. Goddard, L. E. Hutchinson, J. Brown, L. J. Brookman, *Journal of Controlled and Release***1989**, *10*, 5.
- [7] R. Konradi, B. Pidhatika, A. Muhlebach, M. Textort, *Langmuir***2008**, *24*, 613.
- [8] R. Luxenhofer, G. Sahay, A. Schulz, D. Alakhova, T. K. Bronich, R. Jordan, A. V. Kabanov, *Journal of Controlled Release***2011**, *153*, 73.
- [9] K. Knop, R. Hoogenboom, D. Fischer, U. S. Schubert, *Angewandte Chemie International Edition***2010**, *49*, 6288.
- [10] M. Barz, R. Luxenhofer, R. Zentel, M. J. Vicent, *Polymer Chemistry***2011**, *2*, 1900.
- [11] C. Diehl, H. Schlaad, *Macromolecular Bioscience***2009**, *9*, 157.
- [12] M. Talelli, W. E. Hennink, *Nanomedicine***2011**, *6*, 1245.
- [13] M. W. M. Fijten, J. M. Kranenburg, H. M. L. Thijs, R. M. Paulus, B. M. Van Lankvelt, J. De Hullu, M. Springintveld, D. J. G. Thielen, C. A. Tweedie, R. Hoogenboom, K. J. Van Vliet, U. S. Schubert, *Macromolecules***2007**, *40*, 5879.
- [14] E. F. J. Rettler, J. M. Kranenburg, H. M. L. Lambermont-Thijs, R. Hoogenboom, U. S. Schubert, *Macromolecular Chemistry and Physics***2010**, *211*, 2443.
- [15] M. Baumert, J. Zimmermann, J. Scherble, R. Mülhaupt, J. Kressler, *Macromolecules***1999**, *32*, 2503.
- [16] H. Malz, H. Komber, D. Voigt, I. Hopfe, J. Pionteck, *Macromolecular Chemistry and Physics***1999**, *200*, 642.
- [17] H. Malz, J. Pionteck, P. Pötschke, H. Komber, D. Voigt, J. Lustoň, F. Böhme, *Macromolecular Chemistry and Physics***2001**, *202*, 2148.
- [18] I. H. Saegusa T., Fujii H., *Polymer Journal***1973**, *4*, 87.
- [19] M. Litt, A. Levy, J. Herz, *Journal of Macromolecular Science Part A: Pure and Applied Chemistry* **1975**, *9*, 703
- [20] M. E. Kourti, G. C. Vougioukalakis, N. Hadjichristidis, M. Pitsikalis, *Journal of Polymer Science Part A: Polymer Chemistry***2011**, *49*, 2520.
- [21] A. Baumgaertel, C. Weber, K. Knop, A. Crecelius, U. S. Schubert, *Rapid Communications in Mass Spectrometry***2009**, *23*, 756.
- [22] F. Wiesbrock, R. Hoogenboom, M. A. M. Leenen, M. A. R. Meier, U. S. Schubert, *Macromolecules***2005**, *38*, 5025.
- [23] K. Kempe, C. R. Becer, U. S. Schubert, *Macromolecules***2011**, *44*, 5825.
- [24] F. Wiesbrock, R. Hoogenboom, C. H. Abeln, U. S. Schubert, *Macromolecular Rapid Communications***2004**, *25*, 1895.
- [25] C. H. Wang, G. H. Hsiue, *Biomacromolecules***2003**, *4*, 1487.
- [26] C. P. Fik, C. Krumm, C. Muennig, T. I. Baur, U. Salz, T. Bock, J. C. Tiller, *Biomacromolecules***2012**, *13*, 165.

- [27] M. G. Alemseghed, J. Servello, N. Hundt, P. Sista, M. C. Biewer, M. C. Stefan, *Macromolecular Chemistry and Physics***2010**, *211*, 1291.
- [28] R. Weberskirch, J. Preuschen, H. W. Spiess, O. Nuyken, *Macromolecular Chemistry and Physics***2000**, *201*, 995.
- [29] W. H. Binder, H. Gruber, *Macromolecular Chemistry and Physics***2000**, *201*, 949.
- [30] M. Reif, R. Jordan, *Macromolecular Chemistry and Physics***2011**, *212*, 1815.
- [31] L. Buruaga, A. Gonzalez, J. J. Iruin, *Journal of Materials Science***2009**, *44*, 3186.
- [32] T. Saegusa, H. Ikeda, H. Fujii, *Polymer Journal***1972**, *3*, 176.
- [33] P. Buzin, G. Schwarz, H. R. Kricheldorf, *Journal of Polymer Science Part A: Polymer Chemistry***2008**, *46*, 4777.
- [34] M. W. M. Fijten, C. Haensch, B. M. Van Lankvelt, R. Hoogenboom, U. S. Schubert, *Macromolecular Chemistry and Physics***2008**, *209*, 1887.
- [35] A. Cirpan, S. Alkan, L. Toppare, G. David, Y. Yagci, *European Polymer Journal***2001**, *37*, 2225.
- [36] T. Saegusa, H. Ikeda, *Macromolecules***1973**, *6*, 808.
- [37] G. Volet, V. Chanthavong, V. Wintgens, C. Amiel, *Macromolecules***2005**, *38*, 5190.
- [38] R. M. Paulus, C. R. Becer, R. Hoogenboom, U. S. Schubert, *Macromolecular Chemistry and Physics***2008**, *209*, 794.
- [39] J. C. Rueda, H. Komber, J. C. Cedrón, B. Voit, G. Shevtsova, *Macromolecular Chemistry and Physics***2003**, *204*, 947.
- [40] R. Weberskirch, R. Hettich, O. Nuyken, D. Schmaljohann, B. Voit, *Macromolecular Chemistry and Physics***1999**, *200*, 863.
- [41] S. Zalipsky, C. B. Hansen, J. M. Oaks, T. M. Allen, *Journal of Pharmaceutical Sciences***1996**, *85*, 133.
- [42] B. Guillermin, S. Monge, V. Lapinte, J. J. Robin, *Macromolecules***2010**, *43*, 5964.
- [43] C. Giardi, V. Lapinte, F. Nielloud, J. M. Devoisselle, J. J. Robin, *Journal of Polymer Science Part A: Polymer Chemistry***2010**, *48*, 4027.
- [44] C. Weber, J. A. Czaplewska, A. Baumgaertel, E. Altuntas, M. Gottschaldt, R. Hoogenboom, U. S. Schubert, *Macromolecules***2012**, *45*, 46.
- [45] B. Brissault, C. Guis, H. Cheradame, *European Polymer Journal***2002**, *38*, 219.
- [46] S. Cesana, J. Auernheimer, R. Jordan, H. Kessler, O. Nuyken, *Macromolecular Chemistry and Physics***2006**, *207*, 183.
- [47] R. Hoogenboom, M. W. M. Fijten, U. S. Schubert, *Journal of Polymer Science Part A: Polymer Chemistry***2004**, *42*, 1830.
- [48] R. Jordan, K. Martin, H. J. Räder, K. K. Unger, *Macromolecules***2001**, *34*, 8858.
- [49] C. J. Waschinski, V. Herdes, F. Schueler, J. C. Tiller, *Macromolecular Bioscience***2005**, *5*, 149.
- [50] V. Lapinte, J. J. Robin, G. Merenna, C. Colin; *FR 0900559*, **2010**.
- [51] Y. Chujo, E. Ihara, H. Ihara, T. Saegusa, *Macromolecules***1989**, *22*, 2040.
- [52] S. Kobayashi, H. Uyama, Y. Narita, J. Ishiyama, *Macromolecules***1992**, *25*, 3232.
- [53] P. D. Trivedi, D. N. Schulz, *Polymer Bulletin***1980**, *3*, 37.
- [54] B. Guillermin, V. Darcos, V. Lapinte, S. Monge, J. Coudane, J.-J. Robin, *Chemical Communications***2012**, *48*, 2879-2881.
- [55] S. Kobayashi, H. Uyama, T. Mori, Y. Narita, *Chemistry Letters***1991**, *20*, 1771.
- [56] M. Einzmann, W. H. Binder, *Journal of Polymer Science Part A: Polymer Chemistry***2001**, *39*, 2821.

- [57] C. Giardi, V. Lapinte, C. Charnay, J. J. Robin, *Reactive and Functional Polymers***2009**, *69*, 643.
- [58] J. S. Hrkach, K. Matyjaszewski, *Macromolecules***1992**, *25*, 2070.
- [59] K. Pielichowski, J. Njuguna, B. Janowski, J. Pielichowski, "Polyhedral Oligomeric Silsesquioxanes (POSS)-Containing Nanohybrid Polymers", in *Supramolecular Polymers Polymeric Betains Oligomers*, Springer Berlin / Heidelberg, 2006, p. 225.
- [60] M. Einzmann, W. H. Binder, *Macromolecular Symposia***2002**, *181*, 57.
- [61] S. Kobayashi, H. Uyama, Y. Narita, *Macromolecules***1990**, *23*, 353.
- [62] S. Kobayashi, H. Uyama, Y. Narita, *Die Makromolekulare Chemie Rapid Communications***1992**, *13*, 337.
- [63] G. Volet, T. X. Lav, J. Babinot, C. Amiel, *Macromolecular Chemistry and Physics***2011**, *212*, 118.
- [64] R. Luxenhofer, M. Bezen, R. Jordan, *Macromolecular Rapid Communications***2008**, *29*, 1509.
- [65] R. H. Jin, *Journal of Materials Chemistry***2003**, *13*, 672.
- [66] R. H. Jin, *Journal of Materials Chemistry***2004**, *14*, 320.
- [67] J. Stadermann, H. Komber, M. Erber, F. Däbritz, H. Ritter, B. Voit, *Macromolecules***2011**, *44*, 3250.
- [68] H. Uyama, S. Kobayashi, *Macromolecules***1991**, *24*, 614.
- [69] S. Kobayashi, M. Kaku, S. Sawada, T. Saegusa, *Polymer Bulletin***1985**, *13*, 447.
- [70] O. Nuyken, G. Maier, A. Gross, H. Fischer, *Macromolecular Chemistry and Physics***1996**, *197*, 83.
- [71] S. Kobayashi, E. Masuda, S. Shoda, Y. Shimano, *Macromolecules***1989**, *22*, 2878.
- [72] K. Aoi, M. Okada, *Progress in Polymer Science***1996**, *21*, 151.
- [73] R. Hoogenboom, M. W. M. Fijten, U. S. Schubert, *Macromolecular Rapid Communications***2004**, *25*, 339.
- [74] P. Dubois, O. Coulembier, J. M. Raquez, *Handbook of Ring-Opening Polymerization***2009**.
- [75] J. S. Park, Y. Akiyama, F. M. Winnik, K. Kataoka, *Macromolecules***2004**, *37*, 6786.
- [76] G. Volet, A. C. L. Deschamps, C. Amiel, *Journal of Polymer Science Part A: Polymer Chemistry***2010**, *48*, 2477.
- [77] A. Förting, R. Jordan, K. Graf, G. Schiavon, O. Purrucker, M. Tanaka, *Macromolecular Symposia***2004**, *210*, 329.
- [78] R. Hoogenboom, M. W. M. Fijten, M. A. R. Meier, U. S. Schubert, *Macromolecular Rapid Communications***2003**, *24*, 92.
- [79] R. Luxenhofer, R. Jordan, *Macromolecules***2006**, *39*, 3509.
- [80] P. Van Caeter, E. Goethals, V. Gancheva, R. Velichkova, *Polymer Bulletin***1997**, *39*, 589.
- [81] M. Adeli, Z. Zarnegar, R. Kabiri, *European Polymer Journal***2008**, *44*, 1921.
- [82] Y. Chujo, E. Ihara, S. Kure, T. Saegusa, *Macromolecules***1993**, *26*, 5681.
- [83] C. J. Waschinski, J. C. Tiller, *Biomacromolecules***2004**, *6*, 235.
- [84] C. Guis, H. Cheradame, *European Polymer Journal***2000**, *36*, 2581.
- [85] R. L. L. Loontjens T., *Designed Monomers and Polymers***1999**, *2*, 217.
- [86] PCT/US2009/050286,**2010**.
- [87] T. X. Viegas, M. D. Bentley, J. M. Harris, Z. Fang, K. Yoon, B. Dizman, R. Weimer, A. Mero, G. Pasut, F. M. Veronese, *Bioconjugate Chemistry***2011**, *22*, 976.
- [88] A. Mero, Z. Fang, G. Pasut, F. M. Veronese, T. X. Viegas, *Journal of Controlled Release***2012**, *159*, 353.

- [89] D. Christova, R. Velichkova, E. J. Goethals, *Macromolecular Rapid Communications***1997**, *18*, 1067.
- [90] M. Miyamoto, K. Naka, M. Tokumizu, T. Saegusa, *Macromolecules***1989**, *22*, 1604.
- [91] C. Weber, A. Krieg, R. M. Paulus, H. M. L. Lambermont-Thijs, C. R. Becer, R. Hoogenboom, U. S. Schubert, *Macromolecular Symposia***2011**, *308*, 17.
- [92] C. Weber, T. Neuwirth, K. Kempe, B. Ozkahraman, E. Tamahkar, H. Mert, C. R. Becer, U. S. Schubert, *Macromolecules***2012**, *45*, 20.
- [93] G. David, V. Alupeii, B. C. Simionescu, *European Polymer Journal***2001**, *37*, 1353.
- [94] M. C. Woodle, C. M. Engbers, S. Zalipsky, *Bioconjugate Chemistry***1994**, *5*, 493.
- [95] G. David, A. Ioanid, *Journal of Applied Polymer Science***2001**, *80*, 2191.
- [96] A. Groß, G. Maier, O. Nuyken, *Macromolecular Chemistry and Physics***1996**, *197*, 2811.
- [97] C. Weber, C. R. Becer, W. Guenther, R. Hoogenboom, U. S. Schubert, *Macromolecules***2010**, *43*, 160.
- [98] K. Kempe, M. Lobert, R. Hoogenboom, U. S. Schubert, *Journal of Combinatorial Chemistry***2009**, *11*, 274.
- [99] G. Cai, M. H. Litt, *Journal of Polymer Science Part A: Polymer Chemistry***1992**, *30*, 649.
- [100] G. Cai, M. H. Litt, *Macromolecules***1992**, *25*, 2277.
- [101] N. Adams, U. S. Schubert, *Advanced Drug Delivery Reviews***2007**, *59*, 1504.
- [102] K. Kempe, S. Jacobs, H. M. L. Lambermont-Thijs, M. M. W. M. Fijten, R. Hoogenboom, U. S. Schubert, *Macromolecules***2010**, *43*, 4098.
- [103] K. Kempe, M. Lobert, R. Hoogenboom, U. S. Schubert, *Journal of Polymer Science Part A: Polymer Chemistry***2009**, *47*, 3829.
- [104] A. Levy, M. Litt, *Journal of Polymer Science Part A: Polymer Chemistry***1968**, *6*, 1883.
- [105] P. Persigehl, R. Jordan, O. Nuyken, *Macromolecules***2000**, *33*, 6977.
- [106] K. Aoi, A. Takasu, M. Okada, T. Imae, *Macromolecular Chemistry and Physics***1999**, *200*, 1112.
- [107] M. Miyamoto, K. Aoi, M. Morimoto, Y. Chujo, T. Saegusa, *Macromolecules***1992**, *25*, 5878.
- [108] E. Altuntaş, K. Kempe, A. Crecelius, R. Hoogenboom, U. S. Schubert, *Macromolecular Chemistry and Physics***2010**, *211*, 2312.
- [109] R. Luxenhofer, A. Schulz, C. Roques, S. Li, T. K. Bronich, E. V. Batrakova, R. Jordan, A. V. Kabanov, *Biomaterials***2010**, *31*, 4972.
- [110] E. Del Rio, G. Lligadas, J. C. Ronda, M. Galià, V. Cádiz, *Journal of Polymer Science Part A: Polymer Chemistry***2011**, *49*, 3069.
- [111] J. M. Havard, M. Yoshida, D. Pasini, N. Vladimirov, J. M. J. Frechet, D. R. Medeiros, K. Patterson, S. Yamada, C. G. Willson, J. D. Byers, *Journal of Polymer Science Part A: Polymer Chemistry***1999**, *37*, 1225.
- [112] N. Zhang, S. Huber, A. Schulz, R. Luxenhofer, R. Jordan, *Macromolecules***2009**, *42*, 2215.
- [113] T. Kagiya, T. Matsuda, K. Zushi, *Journal of Macromolecular Science Part A: Pure and Applied Chemistry***1972**, *A 6*, 1349.
- [114] R. Hoogenboom, U. S. Schubert, *Green Chemistry***2006**, *8*, 895.
- [115] R. Hoogenboom, *European Journal of Lipid Science and Technology***2011**, *113*, 59.
- [116] V. Schenk, L. Ellmaier, E. Rossegger, M. Edler, T. Griesser, G. Weidinger, F. Wiesbrock, *Macromolecular Rapid Communications***2012**, *33*, 396.
- [117] N. ten Brummelhuis, H. Schlaad, *Polymer Chemistry***2011**, *2*, 1180.
- [118] M. M. Bloksma, C. Weber, I. Y. Perevyazko, A. Kuse, A. Baumgärtel, A. Vollrath, R. Hoogenboom, U. S. Schubert, *Macromolecules***2011**, *44*, 4057.

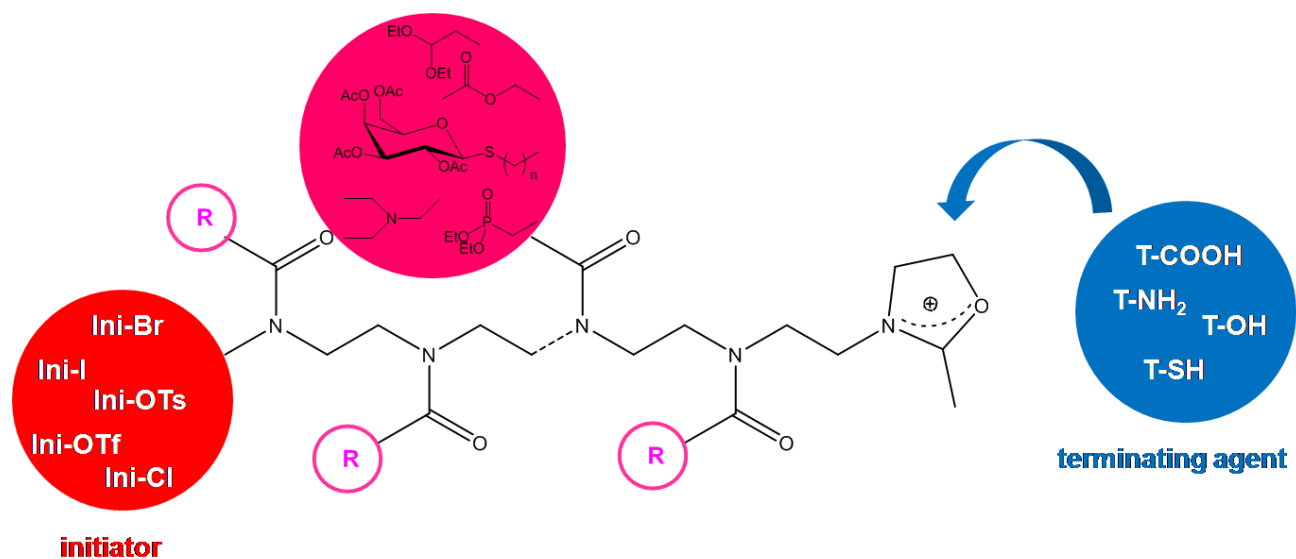
- [119] S. Cesana, A. Kurek, M. A. Baur, J. Auernheimer, O. Nuyken, *Macromolecular Rapid Communications***2007**, 28, 608.
- [120] M. Lobert, H. M. L. Thijs, T. Erdmenger, R. Eckardt, C. Ulbricht, R. Hoogenboom, U. S. Schubert, *Chemistry – A European Journal***2008**, 14, 10396.
- [121] B. R. Hsieh, M. H. Litt, *Macromolecules***1986**, 19, 516.
- [122] M. Miyamoto, M. Shimakura, K. Tsutsui, K. Hasegawa, K. Aoi, S. Yamaga, T. Saegusa, *Macromolecules***1993**, 26, 7116.
- [123] K. Lüdtkke, R. Jordan, P. Hommes, O. Nuyken, C. A. Naumann, *Macromolecular Bioscience***2005**, 5, 384.
- [124] C. Taubmann, R. Luxenhofer, S. Cesana, R. Jordan, *Macromolecular Bioscience***2005**, 5, 603.
- [125] O. Glaied, C. Delaite, G. Hurtrez, M. Joubert, P. Dumas, *Journal of Polymer Science Part A: Polymer Chemistry***2005**, 43, 2440.
- [126] W. H. Binder, R. Sachsenhofer, *Macromolecular Rapid Communications***2007**, 28, 15.
- [127] A. B. Lowe, C. E. Hoyle, C. N. Bowman, *Journal of Materials Chemistry***2010**, 20, 4745.
- [128] K. Kempe, R. Hoogenboom, M. Jaeger, U. S. Schubert, *Macromolecules***2011**, 44, 6424.
- [129] Y. Chujo, K. Sada, T. Saegusa, *Macromolecules***1990**, 23, 2636.
- [130] S. A. Canary, M. P. Stevens, *Journal of Polymer Science Part A: Polymer Chemistry***1992**, 30, 1755.
- [131] J. A. Syrett, C. R. Becer, D. M. Haddleton, *Polymer Chemistry***2010**, 1, 978.
- [132] C. R. Becer, K. Babiuch, D. Pilz, S. Hornig, T. Heinze, M. Gottschaldt, U. S. Schubert, *Macromolecules***2009**, 42, 2387.
- [133] Q. Liu, M. Konas, J. S. Riffle, *Macromolecules***1993**, 26, 5572.
- [134] J. S. Park, K. Kataoka, *Macromolecules***2007**, 40, 3599.

Table of Contents

How to modulate chemical structure of polyoxazolines by appropriate functionalization

Brieuc Guillerm, Sophie Monge, Vincent Lapinte,* Jean-Jacques Robin

Poly(2-oxazoline)s are widely employed as polymeric building block for the obtaining of well defined macromolecular architectures for smart applications. As a consequence, the functionalization of such derivatives is of great interest. The versatility and the diversity of the latter using functional initiators, terminating agents and R pendant chains of the monomers are highlighted in this review.





BriecGuillerm (born in 1983 in Landerneau) obtained his Ph.D. degree in 2011 at the University of Montpellier 2 (France), in the group of Prof. Jean-Jacques Robin at the “Institut Charles Gerhardt de Montpellier”, under the supervision of Dr. Sophie Monge and Dr. Vincent Lapinte. His work dealt with the synthesis and physical chemistry study of amphiphilic copolymers based on polyoxazoline. He is currently a post doctoral researcher in the group of Prof. Philippe Dubois at the University of Mons (Belgium). His general research interests are now the synthesis of poly(ϵ -caprolactone) and polylactide, especially using organocatalyst.



Sophie Monge (born in 1975 in Toulon) obtained her Ph.D. degree in 2000 at the University of Montpellier 2 (France), working in the laboratory of Prof. André A. Pavia and Prof. J. P. Roque on the synthesis of iodine-labeled telomers containing 2-nitroimidazole for the detection of hypoxic tissues and tumors. Then, she was awarded a Marie Curie fellowship for a post-doctoral position (two years) in the group of Prof. Dave Haddleton at the University of Warwick (UK), working on atom transfer radical polymerization. She joined in 2002 the laboratory of Prof. J. J. Robin in the “Institut Charles Gerhardt de Montpellier”. Her research interest mainly focuses on the synthesis of well-defined (co)polymers with stimuli-responsive properties, and with polymers bearing heteroatoms.



Vincent Lapinte (born in 1973 in Tours) obtained his Ph.D. degree in 2003 at the University of Maine (France), working in the laboratory of Prof. Laurent Fontaine on the synthesis and the design of functionalized polymers by ring-opening metathesis polymerization. Then, he obtained a postdoctoral position on the synthesis of polymers based on nitrogen-rich heterocycles in the laboratory of Dr. D. Poullain (CEA, Le Ripault), with the collaboration of Prof. F. Fontaine and Prof J.-F. Pilard. He joined in 2004 the laboratory of Prof. J. J. Robin in the “Institut Charles Gerhardt de Montpellier”. His research interest mainly covers the chemical modification and the use of vegetable oils in polymer field as well as the polyoxazolines.



Jean-Jacques is a full professor of Polymer Chemistry at the University of Montpellier 2, (France). He received his Ph.D. degree in 1985 from the same university. His area of expertise is the synthesis of graft copolymers and the chemical recycling of polymers. He is currently leading the “Ingénierieet Architectures Macromoléculaires” laboratory of the “Institut Charles Gerhardt de Montpellier”.