

**POLY(1,4,5-OXADITHIEPAN-2-ONE)-BASED MATERIALS FOR  
TARGETED DRUG DELIVERY AND SELF-HEALING APPLICATIONS**

**DEBOJIT CHAKRABORTY**



**DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING**

**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**FEBRUARY 2026**

© Indian Institute of Technology Delhi (IITD), New Delhi, 2026

**POLY(1,4,5-OXADITHIEPAN-2-ONE)-BASED MATERIALS FOR  
TARGETED DRUG DELIVERY AND SELF-HEALING APPLICATIONS**

by

**DEBOJIT CHAKRABORTY**

Department of Materials Science and Engineering

Submitted

in fulfilment of the requirements of the degree of

**Doctor of Philosophy**

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**FEBRUARY 2026**

*Dedicated to My Family*

## CERTIFICATE

---

---

This is to certify that the thesis entitled “Poly(1,4,5-oxadithiepan-2-one)-based materials for targeted drug delivery and self-healing applications” being submitted by **Mr. Debojit Chakraborty** to the Indian Institute of Technology Delhi, New Delhi, for the award of degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him. **Mr. Debojit Chakraborty** has worked under my guidance and supervision and has fulfilled the requirements for the submission of heisthesis, which to our knowledge has reached the requisite standard.

The results contained in this thesis are original and have not been submitted, in part or full, to any University or Institute for the award of any other degree or diploma.

**Prof. Josemon Jacob**

Professor

Department of Materials Science and Engineering

Indian Institute of Technology Delhi

Hauz Khas, New Delhi, India – 110016

## ACKNOWLEDGEMENTS

---

The completion of this research work has been made possible with the encouragement, inspiration, and support of several people. I would like to seize this opportunity to sincerely thank the people who have been a part of this memorable journey at IIT Delhi.

First and foremost, I am immensely grateful to my supervisor, Prof. Josemon Jacob, for his invaluable guidance, patience, and encouragement. His expertise and support have been instrumental in shaping my research and ensuring its successful completion. Further, I would like to extend my gratitude and sincere thanks to my student research committee members, Prof. Leena Nebhani, Prof. B. P. Tripathi, and Prof. Rajiv Shrivastava, for their insightful feedback, constructive suggestions, and unwavering support during this process.

I would also like to thank Prof. Jayant Jain, Prof. Anup K. Ghosh, Prof. Rajesh Prasad, Prof. Leena Nebhani, Prof. Bijay P. Tripathi, Prof. Sampa saha, Prof. Suresh Neelakanthan, Prof. Nitya Nand Goswami, Prof. Ankur Goswami, Prof. L. N. Ramasubramanian and all other faculty members of the Department and Materials Science and Engineering who in spite of their busy schedule have always made themselves available for valuable discussions and support.

I would like to thank Prof. Jayanta Bhattacharyya (Centre for Biomedical Engineering, IIT Delhi) and his student Ms. Anindita Sengupta for providing their expertise, research facilities, and invaluable time for the *in vitro* biocompatibility, cellular uptake, and protein adsorption studies.

I owe thanks to the laboratory and office staff, Mr. Jitendra Kumar, Mr. Ashish Sharma, Mr. Gyanendra Kr. Yadav, Mr. Ehteshamul Islam, Mr. Gajraj Singh, Mr. Subhash Chand, Ms. Shalini Arora, Mr. Narender Kumar, Mr. Amit Kumar, Mr. Sudhir Kr. Pandey, and Mr. Pramod Kale for their all possible support and cooperation.

This work would not have been possible without the support of my seniors, Dr. Shubra Goel, Dr. Shikha Baliyan, Dr. Ujjawal Bairagi, Dr. Shivani Goyal, Dr. Umesh Mishra, and Dr. Mahipal Meena. It was a pleasure to share the doctoral journey with my friends and colleagues, Dr. Shaily, Anchal Gupta, Rounak Lama, Kabita Sarkar, Mita Kundu, Akashleena Ghosh, Pradeep R, and Samita Dutta. I want to thank them for their constant support and healthy interactions.

I would like to acknowledge the fellowship provided by the Ministry of Education (MoE), Government of India, which has enabled me to carry out my research work smoothly with financial assistance. I would also like to acknowledge the Science and Engineering Research Board (SERB), Department of Science and Technology (DST), India for providing the grant for my research work. I am also thankful to the Central Research Facility (CRF) and Departmental Research Facility of the Department of Materials Science and Engineering (DMSE), Indian Institute of Technology Delhi (IITD), for providing infrastructural facilities to complete my research work successfully.

On a personal level, I am forever indebted to my family for their unwavering love and support. My wife, Megha, my parents, and all my family members have been my pillar of strength, offering constant encouragement and understanding throughout this journey. Their belief in me has been a source of resilience, guiding me through every challenge. I am deeply grateful to them, whose blessings and faith in me have always been a beacon of inspiration, pushing me to persevere against all odds. This PhD journey has been a challenging yet fulfilling experience, and it would not have been possible without the contributions and support of all the individuals mentioned above. Thank you all for being part of this milestone in my life.



Debojit Chakraborty

## ABSTRACT

---

---

Over the past few decades, there has been a growing interest in the design and development of disulfide-based polymeric materials, with the primary focus on redox responsiveness and self-healing properties. Disulfide-based polymers can be used in drug delivery applications using their redox responsiveness. In the presence of reducing agents such as glutathione, the disulfide bonds in the polymer backbone or cross-links can be reduced to the corresponding thiol groups. With approximately 1000-fold higher concentration of glutathione in tumor cells compared to healthy cells, redox responsiveness enables disulfide-based carriers to degrade rapidly within the cancer cell, resulting in the controlled release of drugs. Polyzwitterionic blocks when attached to disulfide-based polymers can impart pH-responsiveness also for tumor cell-targeted drug delivery. Additionally, polyzwitterionic blocks exhibit antifouling properties during blood circulation to prevent unwanted protein adhesion on the surface of the drug delivery vehicle. Also, disulfide-based polymers can be used for self-healing applications. The self-healing capability results in the extension of the lifespan and the reduction of the need for polymeric material maintenance. Currently, the most promising self-healing polymers are those that are based on dynamic covalent bonds, such as imine bond, disulfide bond, boronic esters, hydrazone bond, etc., for their reversible nature. The disulfide bond is a dynamic covalent bond that facilitates self-healing in polymers under mild conditions in response to a variety of stimuli including heat, light, and pH. In addition, self-healing polymers with shape memory properties have attracted attention due to their potential applications in biomedical devices, electronics, self-healing materials, smart adhesives, etc. Shape memory polymers can be fixed into temporary shapes and revert to their original geometry in response to external stimuli. Thus, the incorporation of disulfide bonds within monomeric units has the potential to produce stimuli-responsive materials. In this thesis, studies on the development of disulfide-based

polymers for redox and pH responsive drug delivery as well as their applications in the design of self-healing shape-memory materials are presented.

In the first section, studies on the synthesis and polymerization of a disulfide-based monomer for redox-responsive drug delivery applications are described. A disulfide-based cyclic lactone, 1,4,5-oxadithiepan-2-one, was prepared from 2-bromoethyl bromoacetate and sodium disulfide. Then, poly(1,4,5-oxadithiepan-2-one) (POD) was synthesized by the ring-opening polymerization of 1,4,5-oxadithiepan-2-one using 1-butanol as the initiator. A diblock copolymer, PEGME-*b*-POD, was prepared by the ring-opening polymerization of POD using polyethylene glycol methyl ether (PEGME) as the macroinitiator. The diblock copolymer was self-assembled into micelles with particle size of ~146 nm and used for redox responsive release studies of the anticancer drug doxorubicin (DOX) in the presence of dithiothreitol (DTT). The drug loading efficiency of the micellar particle was 32% and the maximum cumulative drug release at pH 7.4 was ~98% after 72 h in the presence of 2 mM DTT. The Korsmeyer-Peppas kinetic model suggests that the drug release was diffusion controlled. The micellar particles showed cytocompatibility toward both 4T1 and MCF-7 cells. The cellular uptake of DOX-loaded micelle was higher than free DOX in both 4T1 and MCF-7 cell lines.

In the second section, a polyzwitterionic block, poly(2-(dimethylamino)ethyl methacrylate) (PDMAEMA), was attached to POD to incorporate pH-responsiveness and antifouling properties to the micellar particles. The block copolymer POD-*b*-PDMAEMA was synthesized by ATRP of DMAEMA using POD as the macroinitiator. Then, the tertiary amine groups of the PDMAEMA block was quaternized with bromoacetic acid to prepare POD-*b*-PDMAEMA-Q. The particle size of the copolymeric micelles was found to be in the range of 137-182 nm. Then, POD-*b*-PDMAEMA-Q was converted to the zwitterionic block copolymer, POD-*b*-PDMAEMA-ZIP, in PBS 7.4, and DOX was loaded inside the block copolymeric micelles. The drug loading efficiency of the micellar particles was in the range of 32-51%. The copolymeric

micelles showed maximum cumulative drug release of ~99% at pH 6.5 in the presence of 2 mM DTT. DOX-loaded copolymeric micelles showed cellular uptake and cytotoxicity in 4T1 breast cancer cells, while maintaining cytocompatibility in NIH-3T3 fibroblasts with decreased cellular uptake. The BSA protein adsorption on the surface of the micellar nanoparticles was found to be significantly low. These findings indicate that the disulfide-based redox and pH dual-responsive polyzwitterionic nanoparticles have the potential to deliver targeted anticancer drugs while minimizing harm to normal tissues.

The third section explores the self-healing and shape memory properties of POD-based polyurethane (PU). Two, three, four, and six-arm POD were synthesized by the ring-opening polymerization of the cyclic lactone, 1,4,5-oxadithiepan-2-one, using 1,4-butanediol, trimethylolethane, pentaerythritol, and dipentaerythritol, respectively, as the initiator. The crosslinked PU, POD-PU, was prepared by the reaction between POD and 1,3,5-tris(6-isocyanatohexyl)-1,3,5-triazinane-2,4,6-trione and coated on a glass slide. Then, scratches of 2-17  $\mu\text{m}$  width and 0.7-1.5  $\mu\text{m}$  depth were generated on the surface of all compositions of the POD-PU coating. Scratch healing was observed within 4-8 min at 80  $^{\circ}\text{C}$  when studied using optical microscope and AFM. The estimated healing efficiency ranged from 64% to 96% for the different polyols, as determined by tensile testing. Faster self-healing was observed with increase in the molecular weight of POD, which can be attributed to higher disulfide content. With increase in branches in POD-PU, the tensile strength increased, attributable to the higher crosslink density.

In the triple shape memory studies on POD-PU, the first and second temporary shapes were fixed by varying the temperature from 60 to 25  $^{\circ}\text{C}$  and 25 to -40  $^{\circ}\text{C}$ , respectively, using linear time-dependent stress-strain-temperature programming curves analyzed by DMA. The first and second shape fixity of the polymers were ~65% and 98%, respectively. The first shape recovery was 93-99% and the second one was 70-88% for all arm POD-

PU. It is evident from these findings that disulfide-based polyols are highly prospective materials for the development of polyurethanes with self-healing and shape-memory properties.

In the subsequent section, the self-healing of POD-based poly(urethane-urea) (PUU) was studied. First, POD was prepared with targeted molecular weight of 1500 and 3000 g/mol. POD-PUU was synthesized by the reaction between POD, methylenediphenyl-4,4'-diisocyanate (MDI), and 4,4'-diaminodiphenylmethane (MDA), in which the MDA was used as the chain extender. A scratch was generated on the surface of the film using a laser blade with 15-20  $\mu\text{m}$  width and 0.7-1.4  $\mu\text{m}$  depth, which was healed at 100 °C within 7-9 min. The healing efficiency was 82-87%, measured by the tensile test of healed and uncut samples. A complete shape recovery of the POD-PUU films was observed from thixotropic studies using a rheometer. These results show that the incorporation of disulfide bonds into poly(urethane urea) as in POD-PUU are promising materials for self-healing applications.

## सार

---

पिछले कुछ दशकों में, डाइसल्फ़ाइड-आधारित बहुलक पदार्थों के डिज़ाइन और विकास में रुचि बढ़ी है, जिसका मुख्य ध्यान रेडॉक्स प्रतिक्रियाशीलता और स्व-उपचार गुणों पर है। डाइसल्फ़ाइड-आधारित बहुलकों का उपयोग उनकी रेडॉक्स प्रतिक्रियाशीलता के आधार पर दवा वितरण अनुप्रयोगों में किया जा सकता है। ग्लूटाथियोन जैसे अपचायक एजेंटों की उपस्थिति में, बहुलक आधार या क्रॉस-लिंक में डाइसल्फ़ाइड बंधों को संबंधित थायोल समूहों में अपचयित किया जा सकता है। स्वस्थ कोशिकाओं की तुलना में ट्यूमर कोशिकाओं में ग्लूटाथियोन की लगभग 1000 गुना अधिक सांद्रता के साथ, रेडॉक्स प्रतिक्रियाशीलता डाइसल्फ़ाइड-आधारित वाहकों को कैंसर कोशिका के भीतर तेज़ी से विघटित होने में सक्षम बनाती है, जिसके परिणामस्वरूप दवाओं का नियंत्रित विमोचन होता है। पॉलीज़्विटरियोनिक ब्लॉक, जब डाइसल्फ़ाइड-आधारित बहुलकों से जुड़े होते हैं, तो ट्यूमर कोशिका-लक्षित दवा वितरण के लिए भी pH-प्रतिक्रियाशीलता प्रदान कर सकते हैं। इसके अतिरिक्त, पॉलीज़्विटरियोनिक ब्लॉक रक्त परिसंचरण के दौरान एंटीफ़ाउलिंग गुण प्रदर्शित करते हैं ताकि दवा वितरण वाहन की सतह पर अवांछित प्रोटीन आसंजन को रोका जा सके। इसके अलावा, डाइसल्फ़ाइड-आधारित पॉलिमर का उपयोग स्व-उपचार अनुप्रयोगों के लिए किया जा सकता है। स्व-उपचार क्षमता के परिणामस्वरूप जीवनकाल बढ़ जाता है और बहुलक पदार्थ के रखरखाव की आवश्यकता कम हो जाती है। वर्तमान में, सबसे आशाजनक स्व-उपचार पॉलिमर वे हैं जो गतिशील सहसंयोजक बंधों पर आधारित होते हैं, जैसे कि इमाइन बंध, डाइसल्फ़ाइड बंध, बोरोनिक एस्टर, हाइड्राज़ोन बंध, आदि, अपनी उत्क्रमणीय प्रकृति के कारण। डाइसल्फ़ाइड बंध एक गतिशील सहसंयोजक बंध है जो ऊष्मा, प्रकाश और pH सहित विभिन्न उत्तेजनाओं की प्रतिक्रिया में हल्की परिस्थितियों में पॉलिमर में स्व-उपचार को सुगम बनाता है। इसके अलावा, आकार स्मृति गुणों वाले स्व-उपचार पॉलिमर ने जैव चिकित्सा उपकरणों, इलेक्ट्रॉनिक्स, स्व-उपचार सामग्री, स्मार्ट आसंजकों

आदि में अपने संभावित अनुप्रयोगों के कारण ध्यान आकर्षित किया है। आकार स्मृति पॉलिमर को अस्थायी आकृतियों में स्थिर किया जा सकता है और बाहरी उत्तेजनाओं की प्रतिक्रिया में अपनी मूल ज्यामिति में वापस लाया जा सकता है। इस प्रकार, मोनोमेरिक इकाइयों में डाइसल्फ़ाइड बंधों के समावेश से उत्तेजना-प्रतिक्रियाशील पदार्थ उत्पन्न करने की क्षमता होती है। इस शोध प्रबंध में, रेडॉक्स और pH अनुक्रियाशील औषधि वितरण हेतु डाइसल्फ़ाइड-आधारित पॉलिमरों के विकास पर अध्ययन, साथ ही स्व-उपचारात्मक आकार-स्मृति पदार्थों के डिज़ाइन में उनके अनुप्रयोग प्रस्तुत किए गए हैं।

पहले खंड में, रेडॉक्स-अनुक्रियाशील औषधि वितरण अनुप्रयोगों हेतु डाइसल्फ़ाइड-आधारित मोनोमर के संश्लेषण और बहुलकीकरण पर अध्ययनों का वर्णन किया गया है। 2-ब्रोमोएथिल ब्रोमोएसीटेट और सोडियम डाइसल्फ़ाइड से एक डाइसल्फ़ाइड-आधारित चक्रीय लैक्टोन, 1,4,5-ऑक्साडाइथिएपैन-2-ओन, तैयार किया गया। फिर, 1-ब्यूटेनॉल को आरंभक के रूप में उपयोग करके 1,4,5-ऑक्साडाइथिएपैन-2-ओन के वलय-उद्घाटन बहुलकीकरण द्वारा पॉली(1,4,5-ऑक्साडाइथिएपैन-2-ओन) (POD) का संश्लेषण किया गया। पॉलीइथाइलीन ग्लाइकॉल मिथाइल ईथर (PEGME) को मैक्रोइनिशिएटर के रूप में उपयोग करके POD के रिंग-ओपनिंग पोलिमराइजेशन द्वारा एक द्विब्लॉक सहबहुलक, PEGME-b-POD, तैयार किया गया। द्विब्लॉक सहबहुलक को लगभग 146 नैनोमीटर कण आकार वाले मिसेल में स्व-संयोजित किया गया और डाइथियोथ्रेइटॉल (DTT) की उपस्थिति में कैंसर-रोधी दवा डॉक्सोर्बिसिन (DOX) के रेडॉक्स अनुक्रियाशील विमोचन अध्ययनों के लिए उपयोग किया गया। 2 mM DTT की उपस्थिति में, 72 घंटे बाद, मिसेलर कण की औषधि भारण दक्षता 32% थी और pH 7.4 पर अधिकतम संचयी औषधि विमोचन लगभग 98% था। कोर्सेमेयर-पेपास गतिज मॉडल से पता चलता है कि औषधि विमोचन विसरण नियंत्रित था। मिसेलर कणों ने 4T1 और MCF-7 दोनों कोशिकाओं के प्रति कोशिका-संगतता

प्रदर्शित की। 4T1 और MCF-7 दोनों कोशिका रेखाओं में DOX-भारित मिसेल का कोशिकीय अवशोषण मुक्त DOX की तुलना में अधिक था।

दूसरे खंड में, एक पॉलीज़्विटरियोनिक ब्लॉक, पॉली(2-(डाइमिथाइलएमिनो)एथिल मेथैक्रिलेट) (PDMAEMA), को POD से जोड़ा गया ताकि मिसेल कणों में pH-प्रतिक्रियाशीलता और एंटीफाउलिंग गुण समाहित किए जा सकें। ब्लॉक सहबहुलक POD-b-PDMAEMA को मैक्रोइनिशिएटर के रूप में POD का उपयोग करके DMAEMA के ATRP द्वारा संश्लेषित किया गया। फिर, POD-b-PDMAEMA-Q तैयार करने के लिए PDMAEMA ब्लॉक के तृतीयक अमीन समूहों को ब्रोमोएसिटिक अम्ल के साथ चतुर्धातुकीकृत किया गया। सहबहुलक मिसेल का कण आकार 137-182 nm की सीमा में पाया गया। फिर, POD-b-PDMAEMA-Q को PBS 7.4 में ज़्विटरआयनिक ब्लॉक कोपॉलीमर, POD-b-PDMAEMA-ZIP में परिवर्तित किया गया और ब्लॉक कोपॉलीमरिक मिसेल्स के अंदर DOX लोड किया गया। मिसेल कणों की दवा लोडिंग दक्षता 32-51% की सीमा में थी। 2 mM DTT की उपस्थिति में, कोपॉलीमरिक मिसेल्स ने pH 6.5 पर ~99% की अधिकतम संचयी दवा रिलीज़ दिखाई। DOX-लोडेड कोपॉलीमरिक मिसेल्स ने 4T1 स्तन कैंसर कोशिकाओं में कोशिकीय अवशोषण और कोशिकाविषाक्तता प्रदर्शित की, जबकि NIH-3T3 फ़ाइब्रोब्लास्ट्स में कोशिका अवशोषण में कमी के साथ कोशिकासंगतता बनाए रखी। मिसेलर नैनोकणों की सतह पर BSA प्रोटीन अवशोषण काफी कम पाया गया। ये निष्कर्ष संकेत देते हैं कि डाइसल्फ़ाइड-आधारित रेडॉक्स और पीएच द्वि-प्रतिक्रियाशील पॉलीज़्विटरियोनिक नैनोकणों में सामान्य ऊतकों को होने वाले नुकसान को कम करते हुए लक्षित कैंसर-रोधी दवाएँ देने की क्षमता तीसरा खंड POD-आधारित पॉलीयूरेथेन (PU) के स्व-उपचार और आकार स्मृति गुणों का अन्वेषण करता है। चक्रीय लैक्टोन, 1,4,5-ऑक्साडाइथिपैन-2-ओन, के वलय-उद्घाटन बहुलकीकरण द्वारा क्रमशः 1,4-ब्यूटेनडायोल, ट्राइमेथिलोलेथेन, पेंटाएरिथ्रिटोल और डिपेंटाएरिथ्रिटोल को उत्प्रेरक के रूप में उपयोग करके दो, तीन, चार और छह भुजाओं वाले POD का संश्लेषण किया गया।

क्रॉसलिंकड PU, POD-PU, POD और 1,3,5-ट्रिस(6-आइसोसाइनाटोहेक्सिल)-1,3,5-ट्राइएज़िनेन-2,4,6-ट्रायोन के बीच अभिक्रिया द्वारा तैयार किया गया और एक काँच की स्लाइड पर लेपित किया गया। फिर, POD-PU लेप की सभी रचनाओं की सतह पर 2-17  $\mu\text{m}$  चौड़ाई और 0.7-1.5  $\mu\text{m}$  गहराई के निशान उत्पन्न किए गए। ऑप्टिकल माइक्रोस्कोप और एएफएम का उपयोग करके अध्ययन करने पर 80 °C पर 4-8 मिनट के भीतर खरोंच का उपचार देखा गया। तन्व परीक्षण द्वारा निर्धारित विभिन्न पॉलीओल्स के लिए अनुमानित उपचार दक्षता 64% से 96% तक थी। पीओडी के आणविक भार में वृद्धि के साथ तेज़ स्व-उपचार देखा गया, जिसे उच्च डाइसल्फ़ाइड सामग्री के लिए जिम्मेदार ठहराया जा सकता है। पीओडी-पीयू में शाखाओं में वृद्धि के साथ, तन्व शक्ति में वृद्धि हुई, जो उच्च क्रॉसलिंक घनत्व के कारण थी।

पीओडी-पीयू पर ट्रिपल शेप मेमोरी अध्ययनों में, डीएमए द्वारा विश्लेषित रैखिक समय-निर्भर तनाव-तनाव-तापमान प्रोग्रामिंग वक्रों का उपयोग करके, क्रमशः 60 से 25 °C और 25 से -40 °C तक तापमान को बदलकर पहले और दूसरे अस्थायी आकार को ठीक किया गया था। सभी भुजाओं वाले POD-PU के लिए पहली आकृति पुनर्प्राप्ति 93-99% और दूसरी 70-88% थी। इन निष्कर्षों से यह स्पष्ट है कि डाइसल्फ़ाइड-आधारित पॉलीओल स्व-उपचार और आकृति-स्मृति गुणों वाले पॉलीयूरेथेन के विकास के लिए अत्यधिक संभावित पदार्थ हैं।

अगले भाग में, POD-आधारित पॉली(यूरेथेन-यूरिया) (PUU) की स्व-उपचार का अध्ययन किया गया। सबसे पहले, 1500 और 3000 ग्राम/मोल के लक्षित आणविक भार के साथ POD तैयार किया गया। POD-PUU का संश्लेषण POD, मिथाइलीनडाइफेनिल-4,4'-डाइइसोसायनेट (MDI), और 4,4'-डायमिनोडाइफेनिलमीथेन (MDA) के बीच अभिक्रिया द्वारा किया गया, जिसमें MDA का उपयोग श्रृंखला विस्तारक के रूप में किया गया। 15-20  $\mu\text{m}$  चौड़ाई और 0.7-1.4  $\mu\text{m}$  गहराई वाली लेज़र ब्लेड का उपयोग करके फिल्म की सतह पर एक खरोंच उत्पन्न की गई, जिसे 100 °C पर 7-9 मिनट

में ठीक किया गया। उपचार क्षमता 82-87% थी, जिसे उपचारित और बिना कटे नमूनों के तन्य परीक्षण द्वारा मापा गया। रियोमीटर का उपयोग करके थिक्सोट्रोपिक अध्ययनों से POD-PUU फिल्मों का पूर्ण आकार पुनः प्राप्त हुआ। ये परिणाम दर्शाते हैं कि POD-PUU की तरह पॉली(यूरेथेन यूरिया) में डाइसल्फ़ाइड बंधों का समावेश स्व-उपचार अनुप्रयोगों के लिए आशाजनक सामग्री है। है।



# TABLE OF CONTENT

---

---

CERTIFICATE	i
ACKNOWLEDGEMENTS	iii
ABSTRACT	vi
LIST OF FIGURES	xxii
LIST OF TABLES	xxix
LIST OF SCHEMES	xxxi
LIST OF ABBREVIATIONS AND SYMBOLS	xxxiii
LIST OF CHEMICAL FORMULAE	xxxvii
Chapter 1 Introduction and literature survey	1
1.1 Dynamic covalent bonds	1
1.2 Disulfide-based smart polymers	3
1.2.1 Synthetic approaches to the disulfide bond	3
1.2.2 Redox responsiveness of disulfide-based polymers	5
1.2.3 Disulfide-based multiresponsive polymers	8
1.2.4 Disulfide-based self-healing polymers	12
1.2.5 Disulfide-based self-healing vitrimers	17
1.3 Motivation of the present work	19
1.4 Objectives of the present study	19
1.5 Format of the thesis	20
References	22

<b>Chapter 2</b>	<b>Facile synthesis and polymerization of 1,4,5-oxadithiepan-2-one for disulfide-based redox-responsive drug delivery</b>	<b>39</b>
2.1	Introduction	41
2.2	Results and Discussion	43
2.2.1	Thermal characterization	48
2.2.2	Degradation of PEGME- <i>b</i> -POD in the presence of DTT	50
2.2.3	Estimation of CMC	51
2.2.4	Morphology and particle size	52
2.2.5	Redox-responsive DOX release and kinetics studies	53
2.2.6	<i>In Vitro</i> Cellular Uptake	56
2.2.7	<i>In Vitro</i> Cytotoxicity Assay	57
2.3	Conclusions	59
2.4	Experimental Section	60
2.4.1	Materials	60
2.4.2	Instrumentation and methods	61
2.4.3	Degradation of PEGME- <i>b</i> -POD in the presence of DTT	62
2.4.4	Determination of CMC	62
2.4.5	Encapsulation and release studies of DOX	62
2.4.6	Kinetics and diffusion model for the cumulative release of DOX	63
2.4.7	<i>In Vitro</i> Cytotoxicity Assay	64
2.4.8	<i>In Vitro</i> Cellular Uptake	65
2.4.9	Synthesis	65

2.4.9.1	Synthesis of 2-bromoethyl bromoacetate (BEBA)	65
2.4.9.2	Synthesis of 1,4,5-oxadithiepan-2-one	66
2.4.9.3	Ring Opening Polymerization of 1,4,5-oxadithiepan-2-one	67
2.4.9.4	Synthesis of PEGME- <i>b</i> -POD	67
References		68
<b>Chapter 3</b>	<b>Poly(1,4,5-oxadithiepan-2-one)-based Redox and pH Dual-responsive Polyzwitterionic Micelles for Tumor Cell-targeted Drug Delivery</b>	<b>78</b>
3.1	Introduction	80
3.2	Results and Discussion	83
3.2.1	Determination of <i>pI</i>	87
3.2.2	Estimation of CMC	88
3.2.3	Morphology and particle size	89
3.2.4	Degradation of POD- <i>b</i> -PDMAEMA-ZIP in the presence of DTT	91
3.2.5	Redox and pH dual-responsive DOX release with physico-chemical characterization of DOX-loaded micelles	92
3.2.6	Kinetics of drug release from DOX-loaded micelle	95
3.2.7	<i>In vitro</i> Cellular Uptake	97
3.2.8	<i>In vitro</i> Cytotoxicity Assay	100
3.2.9	Protein Adsorption Studies	101
3.3	Conclusions	102
3.4	Experimental section	103
3.4.1	Materials	103

3.4.2	Instrumentation	104
3.4.3	Determination of CMC	105
3.4.4	Determination of isoelectric point ( <i>pI</i> )	105
3.4.5	Degradation of POD- <i>b</i> -PDMAEMA-ZIP in the presence of DTT	105
3.4.6	Encapsulation and release studies of DOX	106
3.4.7	Kinetics and diffusion model for the cumulative release of DOX	106
3.4.8	<i>In Vitro</i> Cellular Uptake Studies	107
3.4.9	<i>In Vitro</i> Cytotoxicity Assay	108
3.4.10	Protein Adsorption	108
3.4.11	Synthesis	109
3.4.11.1	Synthesis of POD-OH	109
3.4.11.2	Synthesis of POD-Br	110
3.4.11.3	Synthesis of POD- <i>b</i> -PDMAEMA	110
3.4.11.4	Synthesis of POD- <i>b</i> -PDMAEMA-Q	111
3.4.11.5	Conversion of POD- <i>b</i> -PDMAEMA-Q to POD- <i>b</i> -PDMAEMA-ZIP	111
	References	112
<b>Chapter 4</b>	<b>Self-Healing Disulfide-Based Polyurethanes for Coating and Shape Memory Applications</b>	<b>122</b>
4.1	Introduction	124
4.2	Results and Discussion	126
4.2.1	Thermal characterization	130

4.2.2	Self-healing studies	133
4.2.3	Rheological thixotropy studies	136
4.2.4	Mechanical properties	138
4.2.5	Shape memory properties	141
4.3	Conclusions	144
4.4	Experimental section	145
4.4.1	Materials	145
4.4.2	Instrumentation	146
4.4.3	Self-healing studies	146
4.4.4	Rheological thixotropy studies	147
4.4.5	Mechanical test	147
4.4.6	Shape memory properties	148
4.4.7	Synthesis	149
4.4.7.1	Synthesis of two-arm POD	149
4.4.7.2	Synthesis of three-arm POD	149
4.4.7.3	Synthesis of four-arm POD	150
4.4.7.4	Synthesis of six-arm POD	150
4.4.7.5	Preparation of POD-PU coating	151
4.4.7.6	Preparation of POD-PU film	151
References		151

<b>Chapter 5</b>	<b>Disulfide-based poly(urethane-urea) for self-healing application</b>	<b>159</b>
5.1	Introduction	160
5.2	Results and Discussion	162
5.2.1	Thermal characterization	165
5.2.2	Self-healing studies	167
5.2.3	Rheological studies	169
5.2.4	Mechanical properties	171
5.3	Conclusions	173
5.4	Experimental section	173
5.4.1	Materials	173
5.4.2	Instrumentation	174
5.4.3	Self-healing studies	175
5.4.4	Rheological studies	175
5.4.5	Mechanical studies	175
5.4.6	Synthesis	176
	5.4.6.1 Synthesis of POD	176
	5.4.6.2 Synthesis of PUU	176
	References	177
<b>Chapter 6</b>	<b>Conclusions and future outlook</b>	<b>183</b>
<b>Appendix</b>		<b>187</b>
<b>BIODATA</b>		<b>200</b>

## LIST OF FIGURES

---

<b>Figure 1.1</b>	Dynamic bond exchange reactions using (a) associative and (b) dissociative pathways	2
<b>Figure 1.2</b>	(a) Degradation mechanism of disulfide bonds by reduction in the presence of glutathione, (b) tumor cell accumulation of disulfide-based polymeric micelle	6
<b>Figure 1.3</b>	Self-healing of disulfide-based polymer in the presence of external stimuli	13
<b>Figure 2.1</b>	(a) <sup>1</sup> H NMR spectra of BEBA, 1,4,5-oxadithiepan-2-one, POD, and PEGME-b-POD, (b) <sup>13</sup> C NMR spectra of BEBA and 1,4,5-oxadithiepan-2-one	47
<b>Figure 2.2</b>	Mass spectra of (a) BEBA and (b) 1,4,5-oxadithiepan-2-one	48
<b>Figure 2.3</b>	(a) FTIR spectra of BEBA, 1,4,5-oxadithiepan-2-one, POD, and PEGME-b-POD, (b) Raman spectra of 1,4,5-oxadithiepan-2-one and POD	48
<b>Figure 2.4</b>	Thermal characterization of POD and PEGME-b-POD (a) DSC thermogram, (b) TGA, and (c) DTG	49
<b>Figure 2.5</b>	Degradation of PEGME-b-POD in the presence and absence of 2 mM DTT was studied by reduction of molecular weight	50
<b>Figure 2.6</b>	(a) Fluorescence spectra of pyrene at different concentrations and (b) plot of I <sub>337</sub> /I <sub>333</sub> vs logarithm of concentration	51
<b>Figure 2.7</b>	Determination of micellar particle size using (a) DLS before and after drug loading, (b) FESEM	52

<b>Figure 2.8</b>	(a) Fluorescence spectroscopy of DOX in water with different concentrations, (b) calibration curve of DOX of intensity at 590 nm ( $I_{590}$ ) vs concentration	53
<b>Figure 2.9</b>	Redox-responsive DOX release from PEGME- <i>b</i> -POD micelle by fluorescence spectroscopy at different concentrations of DTT (a) 2 mM, (b) 2 $\mu$ M, and (c) control. (d) plot of Cumulative DOX release vs time	54
<b>Figure 2.10</b>	Fitting of experimental DOX release data to different mathematical models (a) Zero-order model, (b) First order model, (c) Higuchi model, and (d) Korsmeyer-Peppas model	55
<b>Figure 2.11</b>	<i>In vitro</i> assays of DOX-loaded micelle. (a) <i>In vitro</i> cellular uptake of free DOX and DOX-loaded micelle by 4T1 cells, MCF-7 cells, and 3T3-L1 was observed under a fluorescence microscope. Scale bar, 200 $\mu$ M. Cytotoxicity of free DOX and DOX-loaded micelles on (b) 4T1 cells and (c) MCF-7 cells post 48h treatment. Measured at 570 nm excitation wavelength	58
<b>Figure 3.1</b>	$^1\text{H}$ NMR spectra of (a) POD, POD-Br, POD- <i>b</i> -PDMAEMA, and POD- <i>b</i> -PDMAEMA-Q, (b) three different proportions of POD- <i>b</i> -PDMAEMA-Q	84
<b>Figure 3.2</b>	(a) FTIR spectra of POD-OH, POD-Br, POD- <i>b</i> -PDMAEMA, POD- <i>b</i> -PDMAEMA-Q, (b) Raman spectrum of POD-OH, and (c) Estimation of <i>pI</i> from zeta potential measurements of quaternized block copolymers	87

<b>Figure 3.3</b>	At pH 7.4, fluorescence spectra of pyrene at different concentrations of (a) POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>1</sub> -Q, (b) POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>2</sub> -Q, (c) POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>0.5</sub> -Q, and (d) plot of I <sub>337</sub> /I <sub>333</sub> vs log C	89
<b>Figure 3.4</b>	FESEM images of (a) POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>0.5</sub> -Q, (b) POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>1</sub> -Q, and (c) POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>2</sub> -Q; diameter of micellar block copolymers POD- <i>b</i> -PDMAEMA-Q measured by DLS before drug loading at (d) pH 7.4, (e) pH 6.5, and (f) pH 5.5; and after drug loading at (g) pH 7.4, (h) pH 6.5, and (i) pH 5.5	90
<b>Figure 3.5</b>	Reduction in $M_n$ of POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>2</sub> -ZIP in the presence and absence of 2 mM DTT	92
<b>Figure 3.6</b>	Zeta potential of POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>0.5</sub> -ZIP, POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>1</sub> -ZIP, and POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>2</sub> -ZIP at pH (a-c) 7.4, and (d-f) 6.5	93
<b>Figure 3.7</b>	Plot of cumulative drug release vs time for (a) POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>2</sub> -ZIP, (b) POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>1</sub> -ZIP, and (c) POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>0.5</sub> -ZIP	95
<b>Figure 3.8</b>	Drug release profile from POD- <i>b</i> -PDMAEMA-ZIP using (a) Zero-order, (b) First order, (c) Higuchi, and (d) Korsmeyer-Peppas models	96
<b>Figure 3.9</b>	<i>In vitro</i> cellular uptake study with DOX-loaded copolymeric micelles. (a,b) Cellular uptake of free DOX and DOX-loaded micelles (POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>0.5</sub> -ZIP, POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>1</sub> -ZIP, and POD <sub>1</sub> - <i>b</i> -PDMAEMA <sub>2</sub> -ZIP) in 4T1 breast cancer cells (a) and NIH-3T3 fibroblasts (b), visualized using fluorescence microscopy. Scale	99

bar: 200  $\mu$ M

- Figure 3.10** *In vitro* cytotoxicity and protein adsorption study. **(a)** *In vitro* cytotoxicity of free DOX and DOX-loaded copolymeric micelles (POD<sub>1-b</sub>-PDMAEMA<sub>0.5</sub>-ZIP, POD<sub>1-b</sub>-PDMAEMA<sub>1</sub>-ZIP, and POD<sub>1-b</sub>-PDMAEMA<sub>2</sub>-ZIP) on 4T1 at different concentrations post 48 h treatment. **(b, c)** *In vitro* cytotoxicity study with micelles. Dose-dependent effects of copolymeric micelles (without the drug) on the viability of 4T1 **(b)** and NIH-3T3 **(c)** cells, assessed using an MTT assay. **(d, e)** Protein adsorption study. The kinetics of absorption of BSA into DOX-loaded micelles at micelle-to-BSA ratios 50:40 **(d)** and 100:40 **(e)**, measured over 30 min, 1, 2, and 6 h. Data are presented as the mean  $\pm$  s.d., n=3 101
- Figure 4.1** <sup>1</sup>H NMR spectra of two-arm, three-arm, four-arm, and six-arm POD 129
- Figure 4.2** Stacked FTIR spectra of (a) POD, (b) POD-PU, and stacked Raman spectra of (c) POD-PU 130
- Figure 4.3** Thermal characterization of different arm POD-PU (a) TGA, (b) DTG, and (c) DSC 133
- Figure 4.4** Self-healing of two-arm POD<sub>1500</sub>-PU at 80 °C after 12 h (a) before healing, (b) after healing, and (c) stretching of the healed strip 134
- Figure 4.5** Self-healing study of two-arm POD<sub>1500</sub>-PU observed by AFM (a) before and (b) after self-healing, and optical microscope (c) before and (d) after self-healing 135
- Figure 4.6** Self-recovery study using thixotropy of (a) two-arm POD<sub>1500</sub>-PU, (b) 137

two-arm POD<sub>3000</sub>-PU, (c) three-arm POD<sub>1500</sub>-PU, (d) three-arm POD<sub>3000</sub>-PU, (e) four-arm POD<sub>1500</sub>-PU, (f) four-arm POD<sub>3000</sub>-PU, (g) six-arm POD<sub>1500</sub>-PU, and (h) six-arm POD<sub>3000</sub>-PU

- Figure 4.7** Tensile test of (a) two-arm POD<sub>1500</sub>-PU, (b) two-arm POD<sub>3000</sub>-PU, (c) three-arm POD<sub>1500</sub>-PU, (d) three-arm POD<sub>3000</sub>-PU, (e) four-arm POD<sub>1500</sub>-PU, (f) four-arm POD<sub>3000</sub>-PU, (g) six-arm POD<sub>1500</sub>-PU, and (h) six-arm POD<sub>3000</sub>-PU 140
- Figure 4.8** Schematic diagram of the triple shape memory programming of shape fixity and the recovery process of POD-PU 142
- Figure 4.9** Triple shape memory study using linear time-dependent stress–strain–temperature programming curves by DMA analysis of (a) four-arm POD<sub>1500</sub>-PU, (b) four-arm POD<sub>3000</sub>-PU, (c) six-arm POD<sub>1500</sub>-PU, and (d) six-arm POD<sub>3000</sub>-PU 143
- Figure 4.10** Qualitative shape memory studies of (a) four-arm POD<sub>1500</sub>-PU, (b) four-arm POD<sub>3000</sub>-PU, (c) six-arm POD<sub>1500</sub>-PU, and (d) six-arm POD<sub>3000</sub>-PU 144
- Figure 5.1** Stacked <sup>1</sup>H NMR of (a) POD<sub>1500</sub> and POD<sub>3000</sub>, and (b) POD<sub>1500</sub>-PUU and POD<sub>3000</sub>-PUU 163
- Figure 5.2** Stacked FTIR spectra of (a) POD<sub>1500</sub> and POD<sub>3000</sub>, (b) POD<sub>1500</sub>-PUU and POD<sub>3000</sub>-PUU, and Raman spectra of (c) POD<sub>1500</sub>-PUU and POD<sub>3000</sub>-PUU 164
- Figure 5.3** TGA and DTGA of (a) POD<sub>1500</sub>-PUU, (b) POD<sub>3000</sub>-PUU, and (c) DSC of POD<sub>1500</sub>-PUU and POD<sub>3000</sub>-PUU 166

<b>Figure 5.4</b>	Images of POD <sub>1500</sub> -PUU (a) before healing, (b) after healing, and (c) stretching of the healed stip. Images of POD <sub>3000</sub> -PUU (d) before healing, (e) after healing, and (f) stretching of the healed stip	168
<b>Figure 5.5</b>	Self-healing images of (a,b) POD <sub>3000</sub> -PUU and (c,d) POD <sub>1500</sub> -PUU using optical microscope. Self-healing images of (e,f) POD <sub>3000</sub> -PUU and (g,h) POD <sub>1500</sub> -PUU using AFM	169
<b>Figure 5.6</b>	Amplitude sweep of (a) POD <sub>1500</sub> -PUU and (b) POD <sub>3000</sub> -PUU. Frequency sweep of (c) POD <sub>1500</sub> -PUU and (d) POD <sub>1500</sub> -PUU and (b) POD <sub>3000</sub> -PUU	170
<b>Figure 5.7</b>	Self-recovery study using thixotropy of (a) POD <sub>1500</sub> -PUU and (b) POD <sub>3000</sub> -PUU	171
<b>Figure 5.8</b>	Tensile test of (a) POD <sub>1500</sub> -PUU and (b) POD <sub>3000</sub> -PUU	172

## LIST OF TABLES

---

---

<b>Table 1.1</b>	Summary of disulfide-based micellar drug delivery systems	11
<b>Table 1.2</b>	Summary of disulfide-based self-healable polymers	16
<b>Table 2.1</b>	Kinetic data of DOX release study from PEGME- <i>b</i> -POD micelle obtained by fitting the experimental release to above mentioned mathematical models	56
<b>Table 3.1</b>	Hydrodynamic diameter of POD- <i>b</i> -PDMAEMA-Q at pH 7.4, 6.5, and 5.5 before and after drug loading	91
<b>Table 3.2</b>	Cumulative drug release at pH 7.4 and 6.5 at different concentrations of DTT for the three drug-loaded copolymeric micelles	94
<b>Table 3.3</b>	Kinetic data of drug release from POD- <i>b</i> -PDMAEMA-ZIP obtained by fitting the experimental release data to the various mathematical models	96
<b>Table 4.1</b>	Summary GPC results of different-arm POD <sub>1500</sub> -PU and POD <sub>3000</sub> -PU	130
<b>Table 4.2</b>	Summary of thermal properties of different arm POD-PU	131
<b>Table 4.3</b>	Summary of scratch healing of different arm POD-PU	135
<b>Table 4.4</b>	Summary of tensile properties of different arm POD-PU before and after self-healing	138
<b>Table 4.5</b>	Summary of the data of the shape memory studies of four and six-arm POD-PU	142
<b>Table 5.1</b>	Summary of thermal properties of POD-PUU	166
<b>Table 5.2</b>	Summary of tensile properties of POD-PUU before and after self-healing	172



## LIST OF SCHEMES

---

<b>Scheme 1.1</b>	Synthesis of disulfide-based monomer, 1,4,5-oxadithiepan-2-one, from mercaptoethanol, followed by polymerization	4
<b>Scheme 1.2</b>	Synthesis of (a) cyclic disulfide from aliphatic dibromide, <sup>45</sup> (b) aromatic disulfide from aromatic bromide	5
<b>Scheme 1.3</b>	Synthesis of disulfide-linked redox and pH dual-responsive block copolymer from PEG and PDMAEMA	9
<b>Scheme 1.4</b>	Self-healing ability of poly(urea-urethane) due to the presence of aromatic disulfide-exchange at room temperature, and the hydrogen bonding between two urea units	15
<b>Scheme 1.5</b>	Synthesis of disulfide-based dynamic epoxy network	18
<b>Scheme 2.1</b>	Synthetic approach toward (a) 1,4,5-oxadithiepan-2-one, (b) POD, and (c) PEGME- <i>b</i> -POD block copolymer	44
<b>Scheme 3.1</b>	Synthesis of POD- <i>b</i> -PDMAEMA-ZIP from 1,4,5-oxadithiepan-2-one	82
<b>Scheme 3.2</b>	Synthetic approach toward POD-OH, POD-Br, POD- <i>b</i> -PDMAEMA, POD- <i>b</i> -PDMAEMA-Q, and POD- <i>b</i> -PDMAEMA-ZIP	83
<b>Scheme 4.1</b>	Synthesis of (a) two-arm, (b) three-arm, (c) four-arm, and (d) six-arm POD-PU	127
<b>Scheme 5.1</b>	Synthesis of POD-PUU from 1,4,5-oxadithiepan-2-one	162



## LIST OF ABBREVIATIONS AND SYMBOLS

---

AFM	Atomic force microscope
ATR IR	Attenuated total reflection infrared
ATRP	Atom Transfer Radical Polymerization
BEBA	2-Bromoethyl bromoacetate
BiBB	2-Bromoisobutyryl bromide
BSA	Bovine serum albumin
CMC	Critical micelle concentration
Da	Dalton
DBTDL	Dibutyltin dilaurate
DCM	Dichloromethane
DDAB	Didecyldimethylammonium bromide
DLE	Drug loading efficiency
DLS	Dynamic Light Scattering
DMA	Dynamic mechanical analysis
DMF	<i>N,N'</i> -Dimethylformamide
DMAP	4-Dimethylaminopyridine
DMSO	Dimethyl sulphoxide
DMSO- <i>d</i> <sub>6</sub>	Deuterated dimethyl sulfoxide
DOX	Doxorubicin
DSC	Differential Scanning Calorimetry
DTG	Derivative thermogravimetry
DTT	Dithiothreitol
FESEM	Field Emission Scanning Electron Microscope

FTIR	Fourier Transform Infrared spectroscopy
g	Gram
GC-MS	Gas Chromatography-Mass Spectrometry
GPC	Gel Permeation Chromatography
GSH	Glutathione
h	Hour
IC50	Half-maximal inhibitory concentration
$K_a$	Dissociation constant for acidic group
$K_b$	Dissociation constant for basic group
LVR	Linear viscoelastic region
MDA	4,4'-Diaminodiphenylmethane
MDI	Methylene diphenyl diisocyanate
min	Minute
$\mu\text{m}$	Micrometre
$\mu\text{g}$	Microgram
$\mu\text{M}$	Micromolar
mg	Milligram
mM	Millimolar
mm	Millimetre
mL	Milliliter
$\mu\text{L}$	Microliter
$M_n$	Number average molecular weight
mol	Mole
mmol	Millimole
MPa	Megapascal

MTT	3-(4,5-dimethylthiazol-2-yl)-2,5-ditetrazolium bromide
MWCO	Molecular weight cut-off
N	Newtons
NMR	Nuclear Magnetic Resonance
OD	Optical density
%	Percent
PBS	Phosphate-buffered saline
PEGME	Polyethylene glycol methyl ether
PDI	Polydispersity Index
PDMAEMA	Poly(2-(N,N-dimethylamino)ethyl methacrylate)
<i>pI</i>	Isoelectric point
PMDETA	N,N,N',N',N'-pentamethyldiethylenetriamine
POD	Poly(1,4,5-oxadithiepan-2-one)
PTSA	p-toluene sulfonic acid
PU	Polyurethane
PUU	Poly(urethane-urea)
Q	Quaternized
R <sub>f</sub>	Shape fixity ratio
R <sub>r</sub>	Shape recovery ratio
sec	Second
ZIP	Zwitterionic polymer
ROP	Ring-opening polymerization
TBAB	Tetrabutylammonium bromide
TEA	Triethylamine
TEM	Transmission Electron Microscopy

$T_{\text{final}}$	Final decomposition temperature
$T_{\text{g}}$	Glass transition temperature
THF	Tetrahydrofuran
$T_{\text{max}}$	Temperature associated with maximum degradation rate
$T_{\text{onset}}$	Initial decomposition temperature
TGA	Thermogravimetric Analysis
TLC	Thin-layer chromatography
TMS	Tetramethylsilane
UTM	Universal testing machine

## LIST OF CHEMICAL FORMULAE

---

$\text{CDCl}_3$	Deuterated chloroform
$\text{CO}_2$	Carbon dioxide
$\text{CuBr}$	Copper(I) bromide
$\text{D}_2\text{O}$	Deuterated water
$\text{NaHCO}_3$	Sodium hydrogen carbonate
$\text{Na}_2\text{S}$	Sodium sulfide
$\text{Na}_2\text{S}_2$	Sodium disulfide
$\text{Na}_2\text{SO}_4$	Sodium sulfate
$\text{S}$	Sulfur
$\text{Sn}(\text{oct})_2$	Tin(II) 2-ethylhexanoate

