Characterisation of multifunctional colloids synthesised via aqueous emulsion polymerisation mediated by macromolecular chain transfer agent (macro-CTA)

Janire Alkorta Salegi

2019

Supervised by Prof.Jose R.Leiza and Dr.Iraida Loinaz

eman ta zabal zazu

UPV EHU

Characterisation of multifunctional colloids synthesised via aqueous emulsion polymerisation mediated by macromolecular chain transfer agent (macro-CTA)

by

Janire Alkorta Salegi

CIDETEC Nanomedicine

eman ta zabal zazu

cidetec>

UPV   EHU

Eskerrak

Lehenik eta behin nire bi zuzendariak eskertu nahiko nituzke. Mila esker bihotzez!! Eskerrik asko Iraida aukera hau emateagaitik eta nigan jarri duzun konfidantzgaitik, eta zuri Joserra behar izan dudan momentu guztietan laguntzeagaitik.

Eskerrik asko/Muchas gracias/Merci Beaucoup a todos mis compañeros de CIDETEC (Aintzane, Julie, Bea, Raquel, Kati, Mireia, Pablo, Adrian, Marcos, Cristian, Susana, Luisa, Ainara, Andrea, Naiara, Yune, Edurne, Marco, Idoia, Luisa, Ana Benito, Xabi, Maria, Aitziber…) Cada uno de vosotros sois parte de esta tesis. En especial quiero agradecer a Laura y a Eider. Me recibisteis con los brazos abiertos cuando no tenía ni idea de lo que era la química. Lo poco que sé es gracias a vosotras. Aunque hemos vivido momentos muy duros, nunca me habéis dado la espalda y habéis estado a mi lado cuando lo he necesitado. Espero no haberos decepcionado. Muchas gracias por cuidarme tan bien estos años. Sin vuestra ayuda esto no hubiese sido posible. Eider, eskerrik asko danaatik!! Ezingoiñat inoiz eskertu!!! Laura, como bien me dijiste un día, esta es tu segunda tesis!! Y luego entraste tú Pikabea. Langile bikaina izateaz gain, zu ohartu gabe gauza pila bat erakutsi dizkidazu. Eskerrik asko!!! Nati, tú has sido mi apoyo emocional en estos cinco años. Sin tus ánimos no habría sido capaz de terminar esta maravillosa tesis. Que suerte tenerte como amiga!! Mil gracias!!

Y por último Damien. El *boss*. Para mi ERES y SIEMPRE SERÁS mi PADRE científico. A parte de ser un trabajador excepcional eres una MARAVILLOSA PERSONA. El otro día, en una exposición fotográfica, me encontré con este texto que hablaba sobre la Preparación: *"Una parte muy importante de la formación se trasmite por canales sutiles y muchas de las habilidades generalmente se aprenden por imitación. Por eso es importante formarse con los mejores…"*. Al instante de leer esta frase, me acordé de ti. Sin duda, para mi tú eres "EL MEJOR". Has despertado en mí curiosidad científica y me has enseñado que con mucho trabajo y humildad uno puede conseguir todo lo que se propone. Si alguien se merece mis agradecimientos, ese eres TÚ.

Tesi hau burutzeko orduan, kimika munduan ondoan izan ditudan lagunez gain, kanpokoen babesa ezinbestekoa izan da. Mila esker TXOBERREKO kide bakoitzari.

Denak hain ezberdin eta hain antzeko aldi berean. Zuek zarete nire altxorrik preziatuena. Mila esker nire lagunak izateagatik.

Eta azkenik, etxekoak. Nere bi txikiak: Naia eta June. Dudarik gabe, azken urte hauetan pasatu zaidan gauzarik politena zarete. Maialen, Aita, Ama. Mila esker zuen babes guztiagatik. Beti sentitu izan naiz oso maitatua. Nirea bai zortea horrelako familia batean jaio izana. Expo, beti nire ondoan, lasai eta goxo. Ikaragarri maite zaituztet.

Nothing in life is to be feared,

it is only to be understood.

General Introduction

When immersed in marine or freshwater, biological macromolecules such as proteins, polysaccharides and proteoglycans start to adsorb on the top of the exposed surfaces. In a second stage, adhered macromolecules are colonized by bacteria, single-cell diatoms, protozoa and rotifer living species, creating a biological film. Finally, micro- and macro-foulers, barnacles, tubeworms and macro-algae, start the colonization of the surface.[1, 2]

For the marine industry, the biofouling makes the hull rougher and ships heavier, increasing the friction resistance. Hence, the fuel consumption of ships can increase up to 40%, resulting in higher costs and more importantly to a dramatic increase of particulate emission, thus pollution, to the atmosphere.[3] Different strategies have been developed to decrease and prevent this type of behaviours. One example is the use of soft and highly hydrophilic materials, such as hydrogels, that exhibit resistance to protein adsorption in relevant conditions.[4] However, due to the low mechanical properties and difficulties to be applied on surfaces, especially large one like for ships and networks, hydrogels are not currently used as coating for marine applications.[5, 6]

Most of the commercially available anti-fouling products on the market are paints based on organic solvent, which result in high level of volatile organic solvents (VOCs) and higher occupational risk for the workers. In On the other hand, waterborne polymer dispersions produced by emulsion polymerisation have been considered as a promising alternative to reduce VOCs and have partially replaced solvent-borne coatings. However, those dispersions are usually obtained with low molecular weight reagents that can migrate during film formation and hence yield some undesirable properties to the final films, as previously reported by Gromer et al.[7] In this context, the synthesis of polymer latexes using non-migratory surfactants or, even, in absence of any surfactant has been an area of growing interest during the last two decades.[8, 9] One approach reported recently is based on the in-situ synthesis of hydrophilic macromolecules that will covalently attach to the polymer particle surface to provide stabilisation and avoid the undesired migration of surfactants.[10] The process requires the synthesis of hydrophilic polymer chains by controlled/living radical polymerisation (CLRP),[11] followed by their chain extensions with hydrophobic monomer via aqueous

emulsion/dispersion polymerisation leading to the formation of amphiphilic block copolymers. These type of copolymerisations, also known as polymerisation-induced self-assembly (PISA)[12-14], have been successfully implemented using various CLRP techniques such as nitroxide-mediated radical polymerisation (NMP)[15], atom transfer radical polymerisation (ATRP)[16] and reversible addition-fragmentation chain transfer (RAFT) polymerisation,[17] with the latter technique easily implemented due to its versatility and simplicity. In that way very high amount of hydrophilic segments could be covalently linked to the particle surface. Also, it allows the surface of the particles to be functionalised by simply adjusting the composition of the hydrophilic macro-CTA and/or controlling copolymers molecular weight with low distribution, which could even modify particles morphology.[18]

In this work, we will explore the use of aqueous emulsion polymerization mediated by macro-CTA strategy to produce well-defined waterborne (nano)particles having high density of covalently linked macro-CTAs to prevent protein adsorption. The technology used in this work is based on the use of water soluble macro-CTAs, containing compounds with antifouling properties, such as, zwitterionic, pseudo-zwitterionic and poly[(oligoethylene glycol) methyl methacrylate] [POEGMA]. Due to the high hydrophilicity of the polymers considered, the corresponding macro-CTAs were used as stabiliser for the aqueous emulsion polymerisation of hydrophobic monomers to obtain aqueous dispersion of polymeric particles.

As a first step, the antifouling properties of those hydrophilic macro-CTAs, i.e.poly(zwitterionic) and poly(pseudo-zwitterionic) (co)polymers, was evaluated by coating a layer via "grafting through" approach on a flat surface. The layer was kept very thin to be in similar condition as when covalently attached to the film-forming particles.

After this proof of concept, the appropriate ratio of hydrophobic comonomers to obtain film-forming stable waterborne polymer dispersions, i.e. with a glass transition temperature (Tg) below 25°C, were produced in the presence of macro-CTA. The presence of the hydrophilic macro-CTA moieties on the surface of the particles was expected to confer antifouling properties to the resulting coatings and prevent protein adsorption.

Finally, using the same copolymerisation strategy, POEGMA macro-CTA was used for the aqueous emulsion polymerisation of styrene, in order to obtain sterically stabilised particles with high Tg (around 100°C), especially prepared for biomedical applications.

It is worth noting that this PhD was carried out in the framework of two EUROPEAN projects called BYEFOULING and OXYPOL where the Biomaterials Unit of CIDETEC Nanomedicine was partner. The main objective of the first project was to design, develop and upscale antifouling coatings with enhanced performance compared to the products currently available on the market.

OXYPOL aimed at developing bio-plastic from lignin-based building blocks to replace similar products produced by the petro-chemical industry that will have positive effects on the environment by reducing CO_2 and toxic chemical emissions. Our group was focused on the production of new functionalised particles to immobilise enzymes on their surface and reduce the adsorption of the proteins to use them in the bioplastic production. The present work was developed in the laboratory of CIDETEC Nanomedicine, in Donostia-San Sebastián, Spain.

The manuscript is divided in five chapters.

Chapter 1 presents the strategy used to synthesise sterically stabilised polymeric dispersions. Also, a bibliographic review on the use of macro-CTA mediated aqueous emulsion polymerisation is reported. Finally, the three mean strategies to synthesise covalently attached monolayers are described.

Chapter 2 focuses on demonstrating that poly(zwitterionic) and poly(pseudo-zwitterionic) layers synthesised via "grafting through" method exhibited similar protein anti-adhesives properties. In addition, the influence of monomers solid content, nature of monomers and linearity of brushes was studied using X-ray photoelectron spectroscopy (XPS) and time-of-flight secondary ion mass spectrometry (ToF-SIMS). The thicknesses of the resulting coatings were measured by XPS, atomic force microscope (AFM) and ellipsometry. The protein resistance properties of the layers were evaluated by an adsorption assay using bovine serum albumin (BSA).

Chapter 3 deals with the optimization of the synthesis of latexes with high solid content, varying some parameters of the reactions such as the nature and degree of polymerisation of the copolymers (macro-CTAs). First of all, poly(zwitterionic) and poly(pseudo-zwitterionic) macro-CTAs were synthesised via reversible addition-fragmentation chain-transfer (RAFT) polymerisation using different RAFT agents. Then, those hydrophilic copolymers were chain extended in aqueous emulsions polymerisation at 10, 20 and 30 wt%. Finally, the resulting film-forming particles properties as antifouling coating were tested in artificial sea water measuring the adsorbed amount of BSA and algae.

Chapter 4 summarises the synthesis of POEGMA homopolymer by RAFT polymerisation, followed by the emulsion polymerisation of styrene monomer, using POEGMA macro-CTA as both, stabiliser and polymerisation control agent. Likewise, the effect of the initiator concentration on the speed and efficiency of the reactions was studied. The resulting particles have been characterised in terms of particle size and zeta potential as a function of pH. Finally, the dispersion cytotoxicity was studied in Human dermal fibroblast cells.

Chapter 5 summarises the most relevant results obtained during this PhD research and addresses some of the challenges encountered in the research and proposes eventual work that could improve the antifouling properties of the aqueous polymer dispersion developed in this work.

Annexe I and **Annexe II** are supplementary sections of **Chapter 2** and **Chapter 3,** respectively. **Annexe III** and **Annexe IV** of **Chapter 4.**

References

1.   L. D. Chambers, K. R. Stokes, F. C. Walsh and R. J. K. Wood, *Surface and Coatings Technology*, 2006, **201**, 3642-3652.
2.   F. Hong, L. Xie, C. He, J. Liu, G. Zhang and C. Wu, *Polymer*, 2013, **54**, 2966-2972.
3.   S. Cao, J. D. Wang, H. S. Chen and D. R. Chen, *Chinese Science Bulletin*, 2011, **56**, 598-612.
4.   N. A. Peppas, J. Z. Hilt, A. Khademhosseini and R. Langer, *Advanced Materials*, 2006, **18**, 1345-1360.
5.   T. R. Hoare and D. S. Kohane, *Polymer*, 2008, **49**, 1993-2007.
6.   M. Parlato, S. Reichert, N. Barney and W. L. Murphy, *Macromolecular bioscience*, 2014, **14**, 687-698.
7.   A. Gromer, F. Thalmann, P. Hébraud and Y. Holl, *Langmuir*, 2017, **33**, 561-572.
8.   E. Aramendia, J. Mallegol, C. Jeynes, M. J. Barandiaran, J. L. Keddie and J. M. Asua, *Langmuir*, 2003, **19**, 3212-3221.
9.   Z. Aguirreurreta, J. C. de la Cal and J. R. Leiza, *Progress in Organic Coatings*, 2017, **112**, 200-209.
10.   E. Velasquez, J. Rieger, F. Stoffelbach, B. Charleux, F. D'Agosto, M. Lansalot, P.-E. Dufils and J. Vinas, *Polymer*, 2013, **54**, 6547-6554.
11.   J. K. D. Mapas, T. Thomay, A. N. Cartwright, J. Ilavsky and J. Rzayev, *Macromolecules* 2016, **49**, 3733-3738.
12.   W. Zhang, F. D'Agosto, O. Boyron, J. Rieger and B. Charleux, *Macromolecules*, 2011, **44**, 7584-7593.
13.   N. P. Truong, M. V. Dussert, M. R. Whittaker, J. F. Quinn and T. P. Davis, *Polymer Chemistry*, 2015, **6**, 3865-3874.
14.   N. J. Warren and S. P. Armes, *Journal of the American Chemical Society*, 2014, **136**, 10174-10185.
15.   J. N. G. Delaittre, C.Lefay, M.Save, B. Charleux, *Soft Matter*, 2006, **2**, 223-231.
16.   H. A. M. M.Obeng, S.M.Muhamad, Z.Cui, A.L.Fielding, R.B.Saunders, L. Farrand, M.Goulding. , *Soft Matter*, 2017, **13**, 2228-2238.
17.   W. Zhang, F. D'Agosto, O. Boyron, J. Rieger and B. Charleux, *Macromolecules* 2012, **45**, 4075-4084.
18.   E. E. Brotherton, F. L. Hatton, A. A. Cockram, M. J. Derry, A. Czajka, E. J. Cornel, P. D. Topham, O. O. Mykhaylyk and S. P. Armes, *J. Am. Chem. Soc.*, 2019, **141**, 13664-13675.

Contents

Chapter 1

Introduction and General Objectives

1.1. Colloids

In 1876 Thomas Graham was the first coning the name "colloid" who borrowed the word from the Greek word "kola" which means glue-like.[1] A colloidal dispersion is a two-phase system, in which one phase (the dispersed phase) is dispersed in a second continuous phase (the dispersion medium). Several classes of colloidal dispersions can be distinguished on the basis of disperse phase and dispersion medium (Table 1.1.)[2]

Table 1.1. Classes of colloidal dispersions.

Dispersed phase	Dispersion medium	Name
Solid	Liquid	Suspension
Liquid	Liquid	Emulsion
Gas	Liquid	Foam
Liquid	Gas	Aerosol
Liquid	Solid	Gel
Solid	Gas	Smoke
Solid	Solid	Composite

Milk is a good example of natural liquid/liquid colloidal dispersion, in which, fat droplets are dispersed in aqueous media stabilised by phosphate groups of the casein protein. One of the most common colloids in modern polymer science and technology are stable colloid dispersions of a polymeric substance called latexes. They can be classified by more than one criterion. The most basic and fundamental classification is into aqueous and nonaqueous colloids. Besides, aqueous latexes can be classified in several ways, but according to origin, there are four main groups: natural, synthetic, artificial and modified latexes. Natural latexes are formed by metabolic processes that occur in plants and trees, meanwhile artificial latexes are formed by dispersing the polymer in aqueous medium and modified latexes are modification of existing type of latexes.[3]

Synthetic latexes are produced by chemical reaction between monomers in emulsion known as emulsion polymerisation and have been utilised commercially since 1929.[4-6] Due to the advantages of emulsion polymerisation such as ability to obtain high molecular weight polymers at high polymerisation rates, maintain the efficient heat dissipation, moderate viscosity increase and the possibility of use water as continuous phase,[7] this industrial process is used in the production of around 15 % of total global synthetic polymers.[8]

1.2.   Emulsion polymerisation

Emulsion polymerisation is a **free radical polymerisation (FRP)** process performed in heterogeneous reaction system.[9] This process is used to produce a wide range of polymers which are mainly used in adhesives, coatings and textile industries.[10-13] To carry out the emulsion polymerisation of relatively hydrophobic monomers, initiator and amphiphilic surfactants and emulsifiers are placed in a heterogeneous aqueous media. This polymerisation process presents distinctive mechanism compared to bulk or solution FRP.[14]

1.2.1. Free Radical Polymerisation (FRP)

FRP technique is one of the most important polymerisation techniques, producing 40-50 % of all industrial polymers.[15] The FRP technique presents unique characteristics compared to ionic polymerisation. For example, it tolerates trace of impurities such as oxygen or/and monomer stabilisers, polymerisation can be carried out in polar solvents (water or alcohols) with monomers that are not rigorously dried or purified.[16]

The mayor industrial monomers contains vinyl units in their structure, and are used to manufacture polymeric materials such as polystyrene, low-density polyethylene, polyvinyl chloride, acrylic polymers, polyvinyl acetate, and synthetic rubbers. Those polymers can be produced by FRP under bulk, emulsion, dispersion and suspension polymerisation conditions. The mechanism of FRP involves three kinetic steps, namely, initiation, propagation and termination as depicted in Figure 1.1.

Initiation

$$I \xrightarrow{k_d} 2R\bullet$$

$$R\bullet + M \xrightarrow{k_i} P_1\bullet$$

Propagation

$$P_n\bullet + M \xrightarrow{k_p} P_{n+1}\bullet$$

Termination

$$P_n\bullet + P_m\bullet \xrightarrow{k_{tc}} D_{m+n}$$

$$P_n\bullet + P_m\bullet \xrightarrow{k_{td}} D_n^{=} + D_m^{H}$$
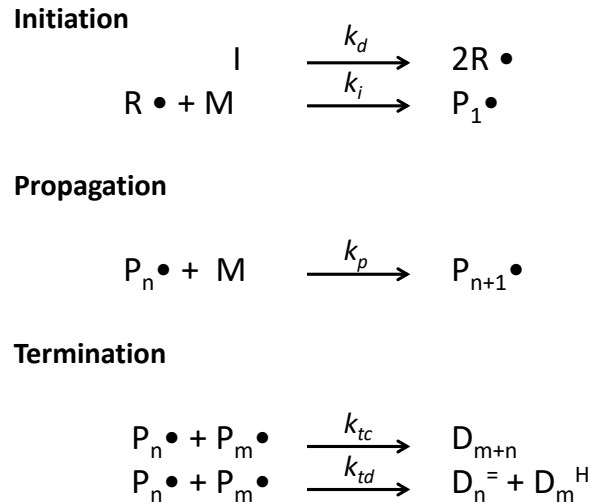
Figure 1.1. Common mechanisms of Free Radical Polymerisation (FRP).

Where I, R•, M, P_n•(n=1, 2, 3,…) and D_n represents the initiator, initiator radical, monomer, free radical polymer with m monomer units and dead polymer chain with m monomer units, respectively. k_d, k_i, k_p, k_{tc} and k_{td} are reaction rate coefficients. k_d, initiator decomposition rate coefficient, k_i and k_p propagation rate coefficient for the free radical and free radical polymer with active monomer units, k_{tc} combination termination rate coefficient and k_{td} disproportion termination rate coefficient between two growing free radicals.

The chain transfer reactions are an additional common aspect of FRP. These transfer reactions occur when the radical activity from a growing chain is transferred to polymer, monomer, solvent or to chain transfer agents (if added). Those reactions reduce the polymers molar mass and hence are usually undesirable (Figure 1.2).

$$P_n\bullet + P_m \xrightarrow{K_{tr,p}} D_n + P_m\bullet$$

$$P_n\bullet + M \xrightarrow{K_{tr,m}} D_n + P_1\bullet$$
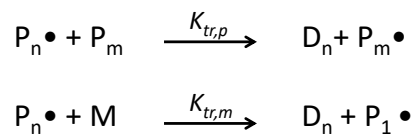
Figure 1.2. Chain transfer of a growing chain to polymer or monomer during FRP.

Where $K_{tr,m}$ and $K_{tr,p}$ are the rate coefficient for the chain transfer reaction of a growing chain with monomer and polymer, respectively.

FRP kinetics can be summarised with the equations (1), (2) and (3). R_i, R_p and R_t are initiation, propagation and termination rates, respectively. f is the efficiency factor (ideally, f is unity) and [I], [M], [P$^\bullet$] and [R$^\bullet$] are the initiator, monomer, polymer radical and initiator radical concentrations, respectively. k_t is the termination rate constant (k_t = k_{tc} + k_{td}).

$$R_i = \frac{d[R^\bullet]}{dt} = 2k_d f[I]$$

(1)

$$R_p = \frac{-d[M]}{dt} = k_p[P^\bullet][M]$$

(2)

$$R_t = \frac{d[P^\bullet]}{dt} = 2k_t[P^\bullet]^2$$

(3)

Assuming that quasi-steady state approximation (QSSA) is valid, namely that the rate of initiation is equal to the rate of termination the concentration of radicals can be calculated as $[P^\cdot] = \left(\frac{fk_d[I]}{kt}\right)^{1/2}$ and the polymerisation rate Rp can be expressed on:

$$Rp = k_p \left(\frac{fk_d}{k_t}\right)^{1/2} [M][I]^{1/2}$$

(4)

However, due to the slow initiation, fast propagation, extensive termination, and transfer reactions, higher molecular weights and broad molecular weights distributions are often yielded by FRP.

In aqueous emulsion polymerisation, initiator, monomers and surfactants are placed in a heterogeneous aqueous media, even though the monomers are not soluble in water.[17] These polymerisations must be carried out with a water-soluble initiator that can be discomposed thermally, photochemically and or by the addition of redox activator, creating radicals in the aqueous phase.[18-20] The radicals react with the monomer until they reach a critical chain length that make then surface active and causing their absorption to micelles, producing polymer particles (co-called heterogeneous or micellar nucleation). In absence of micelles or when more hydrophilic monomers are used, oligoradicals can grow further in the aqueous until they precipitated absorbing monomer and surfactant producing polymer particle (this mechanism is known as homogeneous nucleation). Polymerisation reactions continue inside the micelles, called polymer particles in this part of the process. Particles grow by the gradual entry and consumption of monomer and radicals, and the polymerisation finishes when all monomer is consumed. The polymerisation product is submicrometer-sized polymer particles, dispersed in water and stabilised by surfactant molecules.

Emulsion polymerisation for a systematic description was divided in three intervals by Smith and Ewart[21] built in Harkins theory; Interval I: nucleation of particles; Interval II: growth of the particles and Interval III: end of polymerisation.

Interval I. During the interval I of the emulsion polymerisation, the first radicals and oligoradicals in aqueous phase are produced and they are absorbed into micelles core, to nucleate the first particles. This phase generally goes from 0-15 % of conversion and polymerisation rate is increasing due to the formation of new particles.

Interval II. In this interval new particles are not created and the number of particles (Np) and polymerisation rate are constant. The particles produced in the interval I keep growing by consumption of monomer inside the particles. Monomer droplets work as reservoirs to supply the growing particles with monomer and surfactant. Monomer transport takes place through the aqueous phase and is dictated by a given monomer's water solubility. Interval II is complete when almost all monomer droplets have disappeared and usually the monomer conversion is between 50-60 %

Interval III. Interval III starts after extinction of monomer droplets. The residual monomer inside latex polymerises and usually the small amount of monomer dissolved in aqueous phase can diffuse into polymer particles. Because of gradual decrease of monomer concentration during this interval, the polymerisation rate decreases. The polymerisation reaction ideally continues until all the monomer has reacted. Sometimes the particles can become glassy and the diffusion of the radicals inside of the particles decreases because of Trommsdorff-Norrish effect.[22, 23] The three stages of emulsion polymerisation are summarized in Figure 1.3.
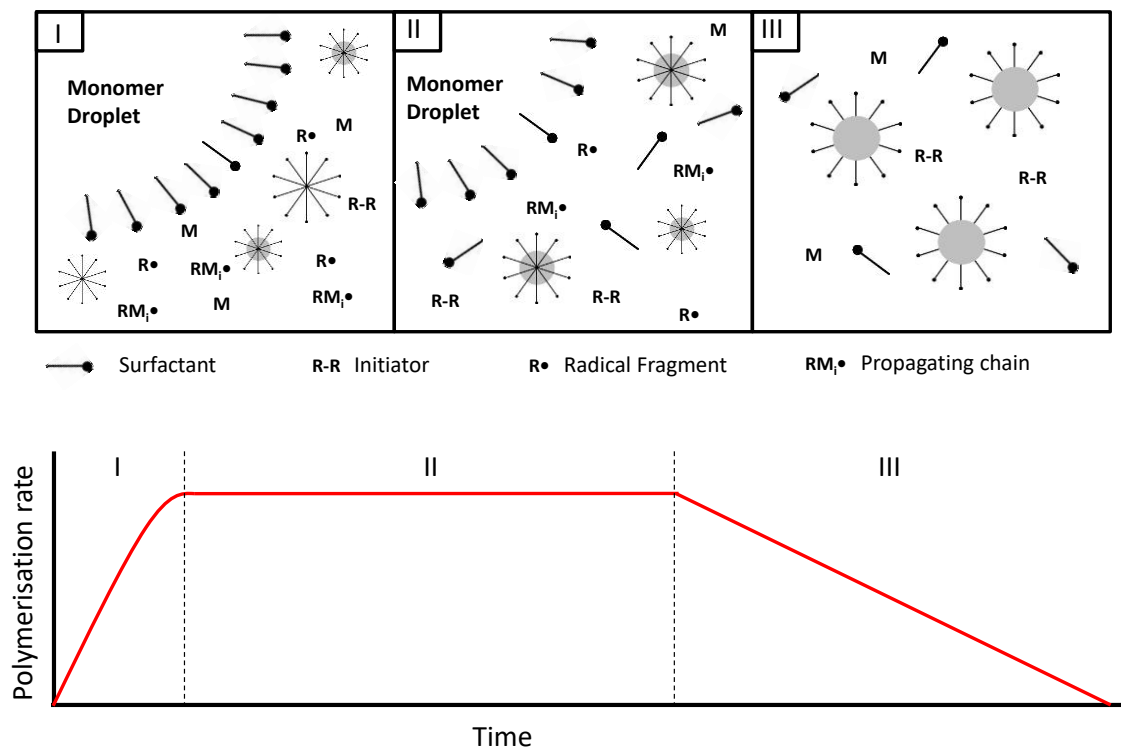
Figure 1.3. Schematic representation of intervals I to III in a typical emulsion polymerisation.[24]

Depending of surfactant concentration, temperature and nature of monomer, different types of nucleation can take place. Nevertheless, Smith and Ewart theory can only be applied to micellar or heterogeneous nucleation.

> *Micellar nucleation.* The micelles are self-assembled spherical conformations created when the concentration of the surfactant is above certain concentration that allow the formation of such structures. In those conditions, the concentration of the surfactants is above Critical Micelle Concentration (CMC) and addition of extra surfactant goes to the stabilisation of the micelles.

The surfactants are non-polar molecules that contain a polar group in their extremity. During the emulsion polymerisation, the hydrophobic part of the molecule is protected by the polar head, that is on the other side, minimising the surface energy. Oligoradicals start growing until they reach a critical size, whereby they lose solubility in water and cause the migration to micelles.[18]

Homogeneous nucleation. Homogeneous nucleation occurs when the oligoradicals do not generate micelle structures but continue growing in the aqueous phase until they reach a critical chain length and chains collide with each other. Then the surfactants are adsorbed on the particles surface, to stabilise created particles. This type of nucleation occurs mainly when the amount of surfactant is not high enough to create micelles or when large concentration of monomer is in the water.[19]

Coagulative nucleation. Some of the particles created during the emulsion polymerisation are not colloidally stable and have difficulties to swell with monomer. These nanometric particles, due to their size and poor electrostatic repulsion, coagulate by van der Waals attraction.[25]

Emulsion polymerisation can be performed by three different processes; batch, semi-batch and continuous emulsion polymerisation.

Batch emulsion polymerisation. Usually the batch emulsion polymerisation is used in laboratory to study reaction mechanisms, develop new latex products and obtain kinetic data for process development and reactor scale up. It is rarely used in industrial plants due to the poor productivity of the process (low solid content), difficulties to control heat exchange and poor reproducibility of the nucleation step. In this process all the reagents are added at the same time before starting the polymerisation.[17]

Semi-batch emulsion polymerisation. Semi-batch emulsion polymerisation is usually carried out in starved monomer feed conditions in which the polymerisation rate is controlled by the feed rate of monomer. The reactor is initially filled with a small amount of monomer and remaining monomer is added continuously at a programmed rate.[26] This technique is widely used in industry because polymer composition,

particles morphology and temperature of the reaction mixture can be controlled varying the composition and amount of the initial charge, likewise changing the composition and flow rate of the feeds.[14] In most of the commercial reactors preformed seed latex is used in the initial period of the reaction. This improves the reproducibility of the process because the nucleation step is avoided.

Continuous emulsion polymerisation. Continuous emulsion polymerisation process consists of 2 to 15 continuous stirred tank reactors connected in series where reagents and products are continuously fed and recovered. Although continuous reactor systems are widely used to produce synthetic latexes, it has some drawbacks such as the cost and complexity of the equipment.[27] Styrene-Butadiene Rubber (SBR) latexes produced for the production of the tyron and other elastomeric goods are produced by this process.

1.2.2. Colloidal stability

By conventional emulsion polymerisation, dispersions comprising a very large population of submicron hydrophobic polymer particles dispersed in the continuous aqueous phase are obtained. Due to the polymer particles and water are immiscible, colloidal dispersions are not thermodynamically stable. To prevent polymer particles aggregation, dispersions can be stabilised by species such as surfactants, polymeric stabilisers or solid particles absorbed on the surface or at the aqueous polymer interface.

Electrostatic stabilisation

The stabilisation of the particles can be achieved by adsorbing electrostatic (or charged) surfactants, initiator or functional monomer at the surface. Charged particles in dispersion have an electrical double layer, which consist in *i*) surface charge, commonly negative and adsorbed on the particle surface, *ii*) stern layer (counterions, compact layer) and *iii*) diffuse layer (a film of the dispersion medium, solvent) (Figure 1.4).[11]
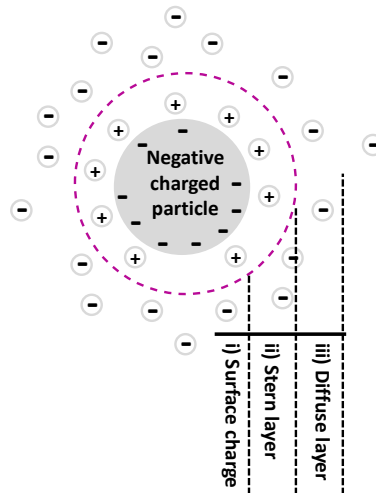
Figure 1.4. Illustration of the electrical double layer of a negatively charged particle.

The balance of the van der Waals attraction and the electric double layer repulsion forces between two adjacent particles determine the stability of the colloidal dispersion.[28]
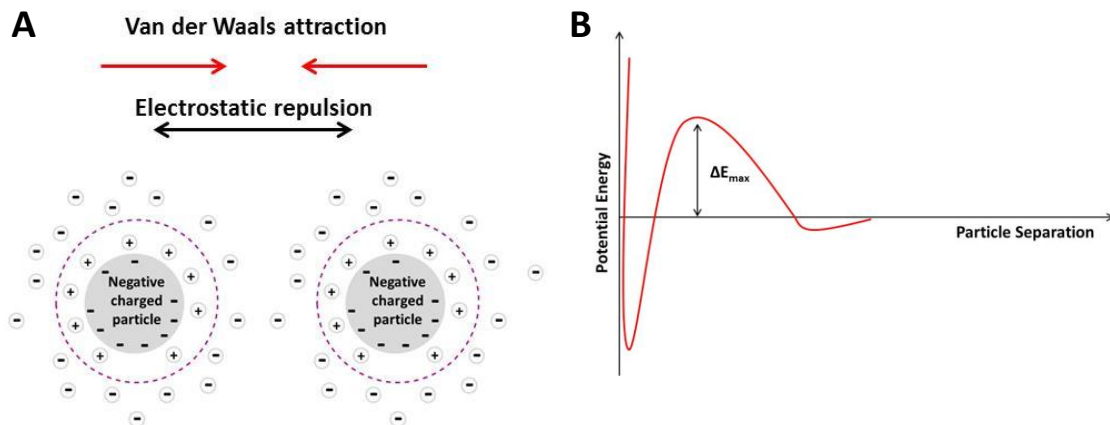
Figure 1.5. Illustration of A) colloid interactions of two negatively charged particles and B) potential energy distance curves.

As shown in Figure 1.5, when the distance of separation between two particles is high, the total potential energy of interaction approaches zero, indicating that van der Waals interactions are insignificant. As the distance of separation decreases, the attractive van der Waals forces tend to aggregate the particles. However, if the total potential energy that creates that electrostatic repulsion forces is high enough, it may avoid the approach of the particles. That activation energy depends on several parameters such as materials in disperse phase, the surface charge density of colloidal particles, the

valence of counterions and the concentration of electrolytes.[14, 29] For example, when the electrolyte concentration is increased, ΔE_{max} is reduced, promoting the particle aggregation.[30]

Steric stabilisation

In addition to electrostatic stabilisation, latex particles can be stabilised by steric stabilisation mechanisms. Steric stabilisers which are physically absorbed or chemically grafted macromolecules, extend themselves into the continuous aqueous phase avoiding the approach of two particles (Figure 1.6). Steric repulsions are a combination of two factors: excluded volume effects and an enthalpic mixing component. Excluded volume effects arise from the loss of conformational entropy of polymer chains because of their interpenetration on close approach of the two particles, and is always repulsive. Mixing component is related to the solvent that prefers the polymer chain to extend. The steric repulsions of two particles depend in the polymer concentration, the polymer chain length and temperature. Likewise, the addition of some solvent and ingredients can destabilise a sterically stabilised dispersion.[11]
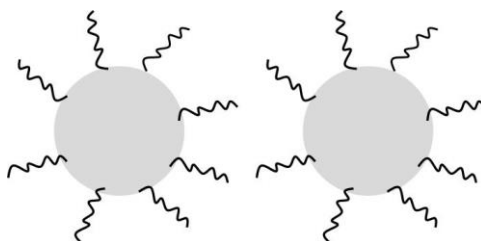
Figure 1.6. Illustration of sterically stabilised particles.

Moreover, steric stabilisation presents more robust features than electrostatic stabilisation; i.e.steric stabilisation is not affected by electrolyte concentration.

Electrosteric stabilisation

Electrosteric stabilisation gives the most stable particles in aqueous media, combining both stabilisation mechanisms previously explained: electrostatic and steric stabilisation. This type of stabilisation can achieve for example using a polyelectrolyte-based stabiliser (Figure 1.7).[31] In commercial formulations this commonly achieved by using small amounts (0.5-2 wt%) of a negatively charged monomers (acrylic and methacrylic monomer).
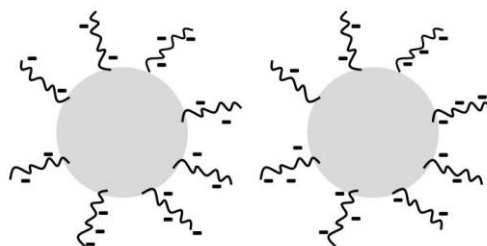
Figure 1.7. Illustration of electrosterically stabilised particles.

1.2.3. Film formation

In latex film formation, the stable colloidal dispersions transform into a continuous polymer film when room temperature is higher than glass transition temperature of the polymer latex.[32] The film formation process of latex dispersions is governed by three stages: drying, deformation and coalescence (Figure 1.8). When the dispersion is applied to a non-porous substrate, the water evaporates from a film of emulsion polymer and the particles start packing (drying). During the deformation stage, van de Waals and capillary forces deform the particles, forming polyhedral cells in the nascent film. Finally, the polymer chains diffuse across the particle-particle interface, creating a film with indistinguishable particles (coalescence).[33]
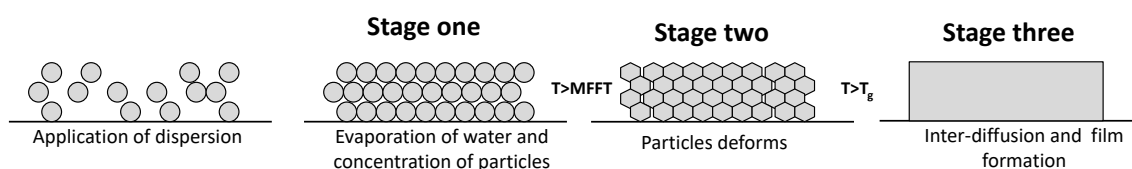
Figure 1.8. Illustration of the three steps of the film formation.

The formation of undivided films is mainly controlled by the free volume of the coatings materials. Above the glass transition temperature of the polymer latexes, the free volume increases (viscosity decreases), increasing the mobility of the polymer chains. Because of that, when the room temperature is higher than glass transition the film formation goes on easier.[14]

As explained previously, surfactants have an essential role in the nucleation and stabilisation of the polymeric particles in emulsion polymerisation process.

Nevertheless, these low molecular substances can produce undesirable effects in the film formation. Surfactants that are adsorbed to the particles surface can migrate to the substrate interface during the film formation. As a consequence, the excess of surfactant can separate phases or even create pockets reducing gloss, adhesion and water sensitivity.[34]

Because of the emulsion polymerisation technique commercial importance, it is still a field of intense research. Since the 1980s, research on heterogeneous systems polymerised by controlled/living radical polymerisation (CLRP) techniques is of high interest. The idea is coupling the advantages of both techniques, CLRP (preparation of well-defined polymer architectures) and water borne polymerisations (cheap, wide range of monomer and conditions, high solid content, etc). Under controlled mechanism, in contrast to free radical polymerisation, the growth time of polymer is equal to the total reaction time and likewise, ideally the bimolecular termination should be eliminated, reducing the concentration of active species. CLRP allows controlling the molar mass and the molar mass distribution of the polymeric chains, and permits to produce complex polymer architectures.

1.3. Controlled/Living Radical Polymerisation (CLRP)

The discovery of living anionic polymerisation by Michael Szwarc[35, 36] facilitated the production of well-defined polymers with precisely designed architectures and nano-structured morphologies.[37-39] The mechanism of living anionic polymerisation was based on the elimination of transfer and termination reactions from chain growth polymerisation with special high vacuum techniques. In 1974, other living techniques such as carbocationic, ring opening metathesis, group transfer, and radical polymerisations were discovered.

Controlled/living radical polymerisation (CLRP), also known as reversible-deactivation radical polymerisation (RDRP, recommended by IUPAC) requires the minimisation of chain breaking and simultaneous growth of all chains. The principle of CLRP[15, 40-42] technique consists on a dynamic equilibrium between active propagating radicals and dormant species (Figure 1.9). The chain-end of the dormant can be activated spontaneously by the presence of catalyst, forming activated specie (active chain). This

process is reversible by deactivating the active species by the capping agent (deactivator). In the dormant state, chains are protected against side reactions typical of free radical polymerisation, such as, combination, disproportionation and transfer. In this way, all the polymers undergo a large number of activation-deactivation cycles throughout the polymerisation, which ensures that all polymer chains experience the same probability to growth. The "living" terms refers to the number of polymer chains that are dormant and can be extended, and "controls" to the number-average molecular weight (Mn) increasing linearly with conversion and Mw/Mn decreasing with increasing conversion.[43]
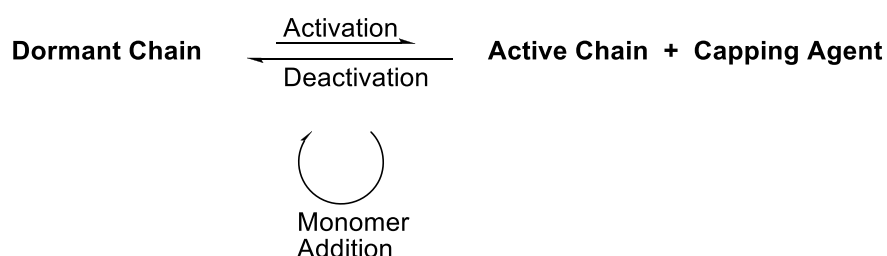
Figure 1.9. Dynamic equilibrium presented in reversible deactivation radical polymerisation mechanism.[44]

Ideally, the bimolecular termination should be eliminated, reducing the concentration of radicals, but it is impossible to avoid those terminations totally. However, they can be minimized by decreasing the number of instantaneous active propagating species. As a result, during the reversible deactivation radical polymerisation the predominant species are the deactivated ones and the life-time of growing chains is significantly increased (Equation 5).

$$\frac{V_t}{V_p} = \frac{[P \bullet]\, k_t}{[M] k_p} \tag{5}$$

Where V_t is the termination rate, V_p is the propagation rate, K_t is the termination rate coefficient k_p is the propagation rate coefficient, [P•] is the concentration of active species and [M] is the monomer concentration.

Reversible termination and degenerative chain transfer are two types of dynamic equilibriums to control the propagation of radicals and various dormant species. Nitroxide-mediated (NMP) and atom-transfer radical polymerisation (ATRP) work under reversible termination, reversible addition-fragmentation chain transfer (RAFT), nevertheless, is based on the second mechanism.[45]

The FRP and CLRP exhibit several important differences to be taken into account. For example, in FRP, almost all the chains are dead, and oppositely, in CLRP, only small fraction of chains (10 % of all chains) is dead due to a large amount of dormant species.[46]

1.3.1. *Nitroxide-Mediated Polymerisation (NMP)*

Nitroxide-Mediated polymerisation was invented in 1993 and is one of the most studied techniques in CLRP.[47] NMP presents some advantages compared to other CLRP technologies. For example, from a mechanistic point of view, NMP is easier than RAFT polymerisation or ATRP technique because metal complexes are not necessary to carry out the polymerisation.[48] Originally, the use of NMP was limited to styrenic monomers,[47] but nowadays, thanks to the development of novel nitroxides and alkoxyamines,[49] it is possible to polymerise other classes of monomers, such as acrylates, methacrylates, acrylamides… Nevertheless, the polymerisation of some of those monomers must be carried out under well-defined conditions, to avoid side reactions and/or slow recombination of the polymer radical with nitroxide. The control in NMP technique method is achieved by reversible termination of the growing polymeric radical by the stable nitroxide free radical (Figure 1.10.).
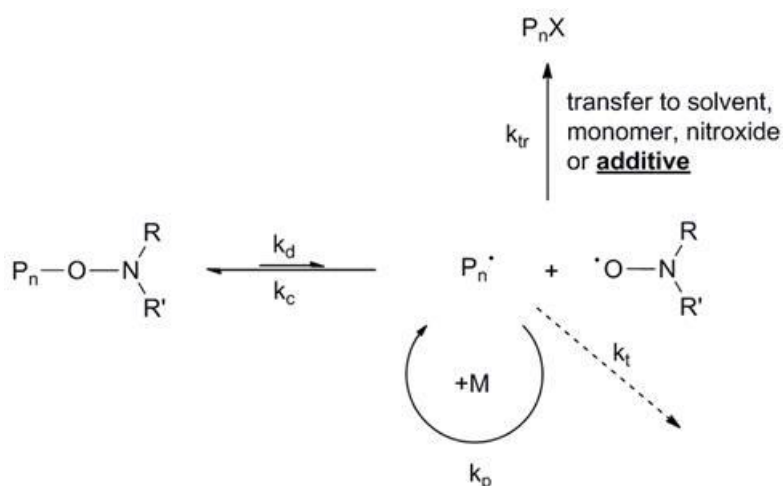
Figure 1.10. Schematic representation of nitroxide mediated polymerisation mechanism. [48]

NMP mechanism is based on the equilibrium between dormant species in which nitroxide is covalently bound to the polymer chain-end ((2,2,6,6-Tetramethylpiperidin-1-yl)oxyl (TEMPO) is the most frequently used alkoxyamine), and the active specie $P_n^{\bullet}$ (the nitroxide is homolytically cleaved). $P_n^{\bullet}$ can propagate by reacting with monomer (M) or it can terminate with other growing radicals. Ideally, the $P_n^{\bullet}$ concentration should be low enough to minimise side reactions, in such a way that they become negligible. It is important to note that optimal values for K = kd/kc (the activation-deactivation equilibrium constant) are directly correlated to K_p (propagation rate constant) and K_t (termination rate constant). K_{tr} is transfer constant. For all the polymer chains to grow at the same time from a macroscopic point of view, it is crucial that the exchange between dormant and active species to be much faster than the propagation and termination steps.[50] Suitable conditions for efficient polymerisation are usually in the range of 80 to 140 °C.[51]

1.3.2. *Atom transfer radical polymerisation (ATRP)*

Atom transfer radical polymerisation (ATRP) mechanism was developed at the same time by Sawamoto[52] and Matyjaszweski[53] in 1995, as a derivation of atom transfer radical addition (ATRA) from organic chemistry polymerisation.

dead chains

$$R \longrightarrow P_n \longrightarrow X \quad + \quad M_t^n \longrightarrow X_n/L \quad \underset{k_c}{\overset{k_d}{\rightleftharpoons}} \quad R \longrightarrow P_n^\bullet \quad + \quad M_t^{n+1} \longrightarrow X_{n+1}/L$$

k_t

M

k_p
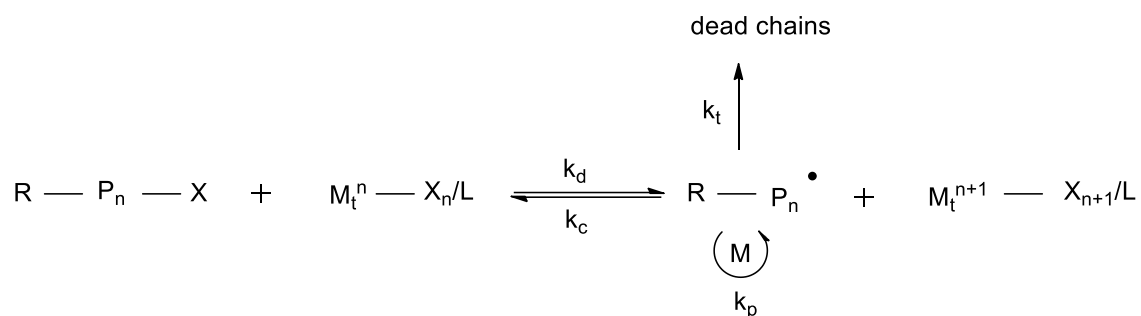
Figure 1.11. Schematic representation of atomic radical polymerisation mechanism. [43]

During this reaction, low oxidation state metal complexes such as Cu^+, are used to activate a dormant species (R-Mn-X), creating a radical R-Mn• and Mt^{n+1} complex (Cu^{2+}). The activated radicals can react with monomer and propagate with further additional monomers or can be deactivated by abstracting the atom from the oxidized complex. Different metals (e.g. Cu, Fe, Ru) are used in combination with various types of ligands to carry out ATRP polymerisations.

1.3.3. Reversible addition-fragmentation chain transfer (RAFT)

Reversible addition fragmentation chain transfer (RAFT) technique can be used in the widest range of radically polymerisable monomers, being the most versatile and convenient CLRP method. Radical addition-fragmentation processes appeared for the first time in early 1970 in organic literature. However, the first polymerisation with reversible addition-fragmentation chain transfer which showed characteristic of living polymerisations were not reported until 1995s.[54] Finally RAFT polymerisation term was coined in 1998 with the use of thiocarbonylthio RAFT agents .[55]

As it was mentioned before, RAFT polymerisation is based on reversible chain transfer reaction in which the equilibrium between radical propagating active and dormant species is controlled by the presence of a chain transfer agent (CTA) that it is a thiocarbonylthio compound, that is also known as RAFT agent (Figure 1.12). The Z group is responsible to activate and deactivate the thiocarbonyl double bond of the RAFT agent. Nevertheless, the R or leaving group, determines the partition coefficient of the RAFT agent. The R group must be a good homolytic leaving group compared to P_n• and fragments, to have a good control over polymerisation. To avoid the consumption of the intermediate species by side reactions, inefficient reinitiation and

retardation or inhibition provide from the slow fragmentation, an appropriate RAFT agent has to be chosen according to the monomer.[56]
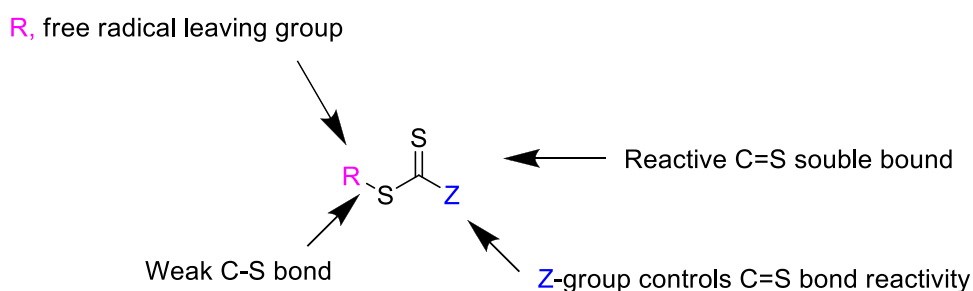
Figure 1.12. Structure of reversible addition-fragmentation chain transfer (RAFT) agent.

Reactions initiate by the decomposition of initiator creating primary radicals. These radicals react with transfer agent molecule **1** by the addition to the thiocarbonylthio group by a weak covalent bond, creating an intermediate radical **2**. This radical will further fragment on the opposite side, ideally, liberating temporary a deactivated species **3** and new active radical, able to initiate the polymerisation. All radicals on their active state can propagate by sequentially adding monomer units, until they encounter a transfer agent **3** and enter the dormant state again **4**. Irreversible termination by combination or disproportionation is also likely to occur at any time. Termination can be minimized by controlling the amount of radicals that are directly related with the initiator concentration. Usually, lower molar initiator concentration than RAFT agent is used ([RAFT]/[Initiator]>1).

Initiation

Reversible chain transfer/propagation

Reinitiation

Chain equilibration/propagation

Termination

Figure 1.13. General mechanism of RAFT polymerisation process.

In the RAFT polymerisation, the molar mass of copolymers is controlled by the stoichiometric relation between monomer and RAFT agent. The molecular weight can be predicted by the following equation:

$$M_{n,th} = \frac{X[M]_0 M_{Mw}}{[RAFT]_0 + df([I]_0(1 - e^{-k_d t}))} + RAFT_{Mw} \tag{6}$$

in which $M_{n,th}$ is the predicted molar mass, X is the monomer conversion, $[M]_0$ is the initial monomer concentration, $[RAFT]_0$ initial RAFT agent concentration, M_{Mw} and $RAFT_{Mw}$ are molecular weights of monomer and RAFT agent, respectively. $[I]_0$ initial concentration at time *t* with a decomposition rate, k_d. The initiator efficiency is

represented by *f*. In an ideal RAFT process, polymer directly derived from the initiator is consider minimal, and thus the second term in the denominator becomes negligible[57] (Equation (7)).

$$M_{n,th} = \frac{X[M]_0 M_{Mw}}{[RAFT]_0} + RAFT_{Mw} \tag{7}$$

Several different transfer agents can be used to control the polymerisation, but the most widely used transfer agents are dithioesteres and trithiocarbonates. They present high versatility polymerising most of the monomers as it shown in Figure 1.14. The RAFT agents that include dithioesters and trithiocarbonates which have carbon or sulfur adjacent to the thiocarbonylthio group are the most reactive agents.
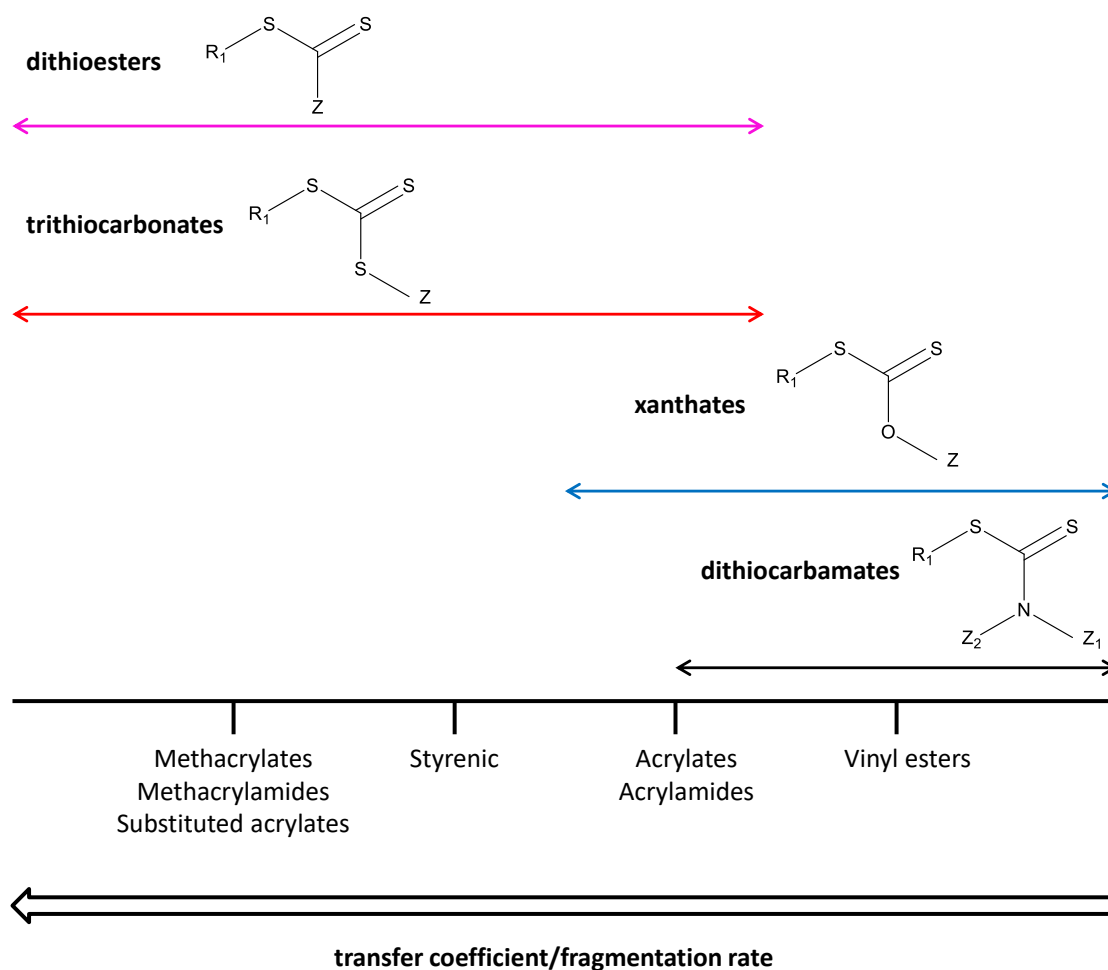
Figure 1.14. Efficiency of various RAFT agents related to the different monomer polymerisation.

The Z group is able to modify the rate of propagating radicals addition (Figure 1.13. 1 and 3 species), as well as, the fragmentation rate of the intermediate radicals (Figure 1.13. 2 and 4 species). By varying the nature of Z group it is possible to adjust by 5 orders of magnitude the addition rate constant k_{add}.[56]

Related to their reactivity, monomers can be classified in two main classes. The "more activated monomers" and "less activated monomers". In the first group, the double bond is conjugated to an aromatic ring (e.g. styrene), a carbonyl group (e.g.methyl methacrylate), or a nitrile group (e.g. acrylonitrile). However, less activated monomers are those, where the double bond is adjacent to a saturated carbon (e.g. diallyldimethylammonium chloride), oxygen (e.g. vinyl acetate) nitrogen pair (e.g. N-vinylpyrrolidone) and a heteroatom of a heteroaromatic ring (e.g. N-vinylcarbazole). Propagating radicals with a more active terminal monomers present low reactivity

towards radical addition and high rate of radical fragmentation, implying that more reactive RAFT agent is required, such as, dithioesters, trithiocarbonates and aromatic dithiocarbamates. Nevertheless, propagating radicals with less-activated terminal monomers present high reactivity to radical addition and weak fragmentation rate. For this reason, addition to less active transfer agents such as N-vinylpyrrolidone is sufficient to have RAFT agent with high transfer constant during the polymerisation.[56]

Concerning the role of the R group, it determines the partition coefficient, and the choice of R group nature depends on the monomer to be polymerised.[58] To optimally control the polymerisation, the R group of RAFT agent must be a good homolytic leaving group with respect Pn•, in favour of R• and 3rd specie formation (Figure 1.13). The stability, steric hindrance and polarity are very important elements to determine fragmentation factors. The efficiency of different R groups as a leaving groups are summarised in Figure 1.15.
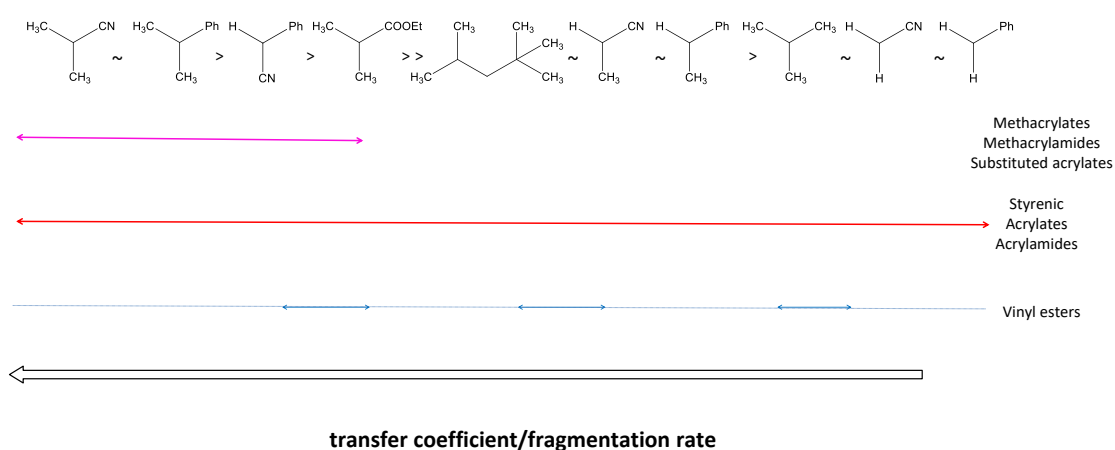

transfer coefficient/fragmentation rate

Figure 1.15. Summary of the efficiency of the R group as a leaving group with different monomer polymerisations. When the line is dash means that the control is partial. [59]

In the literature, plenty of articles related to CLRP method explain NMP, ATRP and RAFT operating mechanism with more details.[60, 61 62]

1.4. Reversible addition-fragmentation chain transfer (RAFT) in Dispersed systems

All controlled polymerisation techniques are applied to both homogeneous and (bulk/solution) polymerisations, as well as, heterogeneous dispersed media. The interest in this topic and the amount of the works published related to RAFT have increased in the last decades.[62-64] However, some difficulties have been observed when the technology was transferred from homogeneous to heterogeneous polymerisations. The kinetics of heterogeneous polymerisations become more complicated by partition of the activating species in the various environments and by the rate of transportation of these species and larger dormant ones to the reaction locus, aqueous phase reactions, choice of surfactant and control of the particle size distribution.[65]

1.4.1. RAFT miniemulsion polymerisation

Theoretically, in an ideal situation of miniemulsion polymerisation, each monomer droplet transforms into polymer particle. However, due to Ostwald ripening and coalescence, it is difficult to produce polymer particles under that ideal situation.[66] In miniemulsion polymerisation, homogenisation is achieved applying intensive shear forces or an energy whereby the droplets of emulsions are broken.[67] Use an efficient surfactant and water insoluble low molecular weight compounds as co-stabiliser can decrease coalescence and Ostwald ripening phenomena. Compared to traditional emulsion polymerisation, the most important diction is the nucleation mechanism. In the miniemulsion polymerisation, the radicals created in the water phase enter in monomer droplets to initiate polymerisation inside of the droplets, and droplets become to polymer particles (droplets nucleation mechanism).[67]

To carry out typical miniemulsion polymerisation, water, the monomer mixture, a co-stabiliser, surfactant and initiator are placed in the reactor. Nevertheless, the use of those conventional stabilisers is undesirable and because of that, in the literature we can find several articles of such surfactant free systems. So far, minimemulsion by RAFT polymerisation was carried out with huge number of monomers such as styrene, n-butyl acrylate, methacrylic acid, etc.[68] From an industrial point of view, miniemulsion

polymerisation presents some attractive features, creating copolymers of uniform coatings and latexes with excellent shear capacity. [69] However, commercial products produced by miniemulsion polymerisation are not frequent nowadays. In 2014, Professor Asua published an article in which some of the main reasons why industrialisation of minimeulsion polymerisation has been delayed are reported.[70]

1.4.2. RAFT dispersion polymerisation

Traditional dispersion polymerisation is a heterogeneous polymerisation reaction in which the monomers are soluble in continuous phase, but not the resulting polymers. The polymerisation proceeds in continuous phase, which usually is a solution of water and alcohol and as a function of the polymeric chains being formed, precipitate and aggregate to form particles stabilised with surfactants or stabilisers. Even though the particle size is controlled by the concentration and nature of surfactants, usually the particles diameter obtained by dispersion polymerisation is higher than in conventional emulsion polymerisation.[67]

RAFT polymerisation also has been applied on dispersion polymerisation. The preliminary works were carried out using low molecular weight RAFT agents.[68, 71] For example, polystyrene microspheres were synthesised in alcoholic media using poly(N-vinylpyrrolidone) as stabiliser by Saikia et al.[72] in 2007. On the basis of those previous works, in the last decade huge amount of articles have been published that study different parameters influence, such as, solvents, initiator, nature of macromolecular chain transfer agents (macro-CTA), etc.[73-75] It is noteworthy that P. Armes at co-workers, have published vast number of articles about RAFT aqueous dispersion polymerisation in the last decade, in which they analysed the influence of volume fraction of hydrophilic and hydrophobic blocks fractions in final morphology. Furthermore, besides of vesicles, spheres and worms[76-81] other unusual morphologies have also been reported by polymerisation-induced self-assembly (PISA), such as lamellae,[82] framboidal vesicles,[77] spaced concentric vesicles,[83] yolk/shell particles[84] and doughnuts.[85]

Even though most of the works on dispersion polymerisation have been carried out via PISA strategy and with considerable solid content (10-40 wt %), usually obtained

polymer particles diameters were higher than in emulsion polymerisation mediated by macro-CTA.

1.4.3. RAFT emulsion polymerisation

Kinetics of conventional emulsion polymerisations are highly complex. The main difficulties have been in maintaining colloid stability, achieving reasonable reaction rates and controlling molecular weight distribution.[86, 87] The problems observed were minimized using seed emulsion polymerisation by Prescott at al.[88] and ab initio polymerisation strategies by Ferguson et al[89] in RAFT emulsion polymerisation.

Concerning ab-initio RAFT emulsion polymerisation two general approaches have been utilised. **Conventional approach[90-92]**, stabilised by conventional surfactant and using RAFT agent with free radical initiators and **self-assembly,[63, 89, 93-95]** in which the living amphiphilic copolymers chains are used as macroinitiators and stabilisers. Comparing both techniques, the last approach provides more control over the polymerisation, although its complexity is higher.

Polymerisation-induced self-assembly (PISA) RAFT emulsion polymerisation.

As it was mentioned before, Ferguson et al.[89] were the first developing polymerisation induced self-assembly. They used an amphiphilic RAFT, which can carry out polymerisation in aqueous and organic phase. Firstly, water-soluble acrylic acid (AA) monomer was polymerised in water obtaining a polymer with low polymerisation degree (AA_x-RAFT). In the next step, butyl acrylate (BA) hydrophobic monomer was added under controlled feed, to give oligomers $(AA)_x$-$(BA)_y$-RAFT, which form rigid micelles. By the continuous monomer feed, micelles were further swollen, achieving polymer chains with molar masses in agreement with theoretical values and narrow molar mass distributions. One of the advantages that this technique presents is the absence of additional stabiliser, due to $(AA)_x$-RAFT provides stability.

In RAFT emulsion polymerisation, using water soluble macromolecular chain transfer agents (CTA), competition between self-assembly nucleation and homogeneous nucleation might occur.[59] In the first one, amphiphilic oligoradicals formed from the reaction of the hydrophobic monomer with the macro-CTA would form block

copolymers, which could self-assemble to form particles. However, the second mechanism consisted in conventional homogeneous nucleation, derived from the precipitation of oligoradicals created independently of the macro-CTA. Manguain et al.[96] showed the successful production of polystyrene latexes through poly(2-(diethylamino)ethyl methacrylate) (PDEAEMA) macro-CTA. Stable latexes with relatively small particles diameters were obtained and they concluded that the polymerisation induced self-assembly mechanism was the main mechanism, independently of the amount of initiator.

In the following years, some important steps were done performing both, amphiphilic block copolymer and emulsion polymerisation in water (one-pot process). Bernadettte Charleux and co-workers[97] implemented one-pot process, showing the successful efficiency of the system to obtain amphiphilic block copolymers. They carried out RAFT (co)polymerisation of methacrylic acid (MAA), poly acrylic acid (AA) and (ethylene oxide)methyl ether methacrylate ($EO_{18}MA$) (co)monomers, and immediately in the same flask styrene emulsion polymerisation was produced. In this context, the kinetics and mechanism of amphiphilic P(MAA-co-PEOMA)-b-PS block copolymers and their self-assembled in water were examined also by Zhang et al.[98] In the next years, the laboratory of Chemistry, Catalysis, Polymers and Process of Lyon continued analysing the effects of different parameters, such as, pH[99], hydrophilicity,[100] monomers composition,[101] among others.

Until 2010, only nanospherical particles were reported by RAFT emulsion polymerisation. Nevertheless, playing with the nature and structure of the macro-CTA, other morphologies were produced. In the first article published by Stephanie Boisse et al.,[102] they synthesised a series of well-defined poly(acrylic acid)-co-poly(ethylene glycol)methyl ether acrylate RAFT agents using 2-(dodecylthiocarbonothioylthio)-2-methylpropanoic acid (TTCA) RAFT agent followed by polystyrene block polymerisation in-situ at different pH and salt concentration. In appropriate conditions of pH and salt concentrations very long nanofibers (>1 μm) were obtained.

In 2011, Stephanie Boisse et al.,[103] taking as reference the previously published system,[102] studied further parameters that may influence and control the particles

morphologies, such as stirring speed and the presence of divalent salts. To change the nature and amount of salts, and slow down or accelerate the stirring speed, allowed the formation of various morphologies in a controlled manner. In that way, from very small and homogenous spheres, to long filaments or vesicles-like structures were achieved.

One of the most important advantages of PISA formulations is that it is possible to produce dispersion with relatively high solids contents (25-50 wt%).[77, 104, 105] However, so far, little attention has been paid to produce such industrially relevant colloidal formulations, in not controlled conditions ([I] >[RAFT]). In 2005, Manguain et al published an article related to this process,[96] in which they analysed the influence of initiator in batch emulsion polymerisation stabilised by hydrophilic macro-CTA. They concluded that in both cases, controlled ([I] < [RAFT]) and no controlled conditions ([I] >[RAFT]), emulsion polymerisation mediated by macro-CTA was the main mechanism, and not as much homogeneous nucleation, as it was expected at the beginning. Two years later, Amilton Martins dos Santos and co-workers[106] demonstrated the anchoring of the polyethylene glycol (PEO) macro-CTA to polystyrene surface, using higher molar amount of initiator than macro-CTA (not controlled conditions). However, until recently, not so much attention has been paid to this strategy. Recently, industrially relevant latex particles at 40 wt % have been fabricated using macro-CTAs[107-109] as stabilisers. Firstly, Velasquez et al.,[107] carried out vinylidine chloride (VDC) and methacrylic acid (MA) comonomers emulsion copolymerisations of high solid content (40 wt%) using very low amount of (tipically < 2 wt% with respect to monomer) hydrophilic macro-CTA. Three different macro-CTAs were used (poly(methyl methacrylate) (PMA), poly(acrylic acid) (PAA) and poly(sodium 4-styrenefulfonate) (PSSNa)) to produce stable film-forming particles. However, PAA presented poor efficiency of the chain transfer reaction at low MAA concentration ($\leq$ 8.5 wt%). PMAA and PSSNa agents led to a much more efficient chain transfer reaction observing faster and a more efficient nucleation. PMAA and PSSNa macro-CTAs attachment to the particles was demonstrated measuring the superficial tension of the films and maintaining the transparency of films when immersed in water.[107] Likewise, the concept of polymerisation-induced self-assembly was advantageously used to

synthesise film-forming latexes via surfactant-free emulsion polymerisation by Lesage de la Haye et al. [108] Methyl methacrylate (MMA), n-butyl acrylate (BA) and styrene (S) (co)monomers aqueous emulsion (co)polymerisation (40 wt%) mediated by water soluble PMAA macro-CTA (≤ 1.5 wt%) were carried successfully (low amount of coagulum and particle size in the 100-200 nm range). In addition different ccross-linking strategies were applied to these formulations. Films properties were examined measuring the amount of water uptake, analysing the opacity by ultraviolet-visible or testing particles coalescence by atomic force microscopy. The film that was cross-linked by diacetone (DAAm) and adipic acid dihydrazide (ADH) external cross-linker strategy provides the preferred mechanical properties.

1.5. Antifouling approaches

The covalent attachment of the macro-CTAs to the surface of the particles could provide to the films additional properties. For example, Damien Quemener and co-workers synthesised via RAFT polymerisation,[110] well-defined and anti-bioadhesive block copolymers of poly{[(2-(methacryloyloxy)ethyl)trimethylammonium chloride]-co-[(3-sulfopropyl methacrylate potassium]} (P(TMAEMA)-co-(SPMA)), to prevent the adsorption of fibrinogen, lysozyme and bovine serum albumin (BSA). These copolymers could be used such as blood filtration membranes or blood containers. Likewise, by comparing the results with previously reported poly[(2-methacryloyloxy)ethyl dimethyl-(3-sulfopropyl)ammonium hydroxide] (P(SBMA)) coatings, they demonstrated that the pseudo-zwitterionic copolymers properties as blood inert material were similar to zwitterionic sulfobetaine polymers. The advantages that zwitterionic compounds present in the area of anti-biofouling[111, 112] and protein resistance[113] are well known. Zwitterionic are neutral materials that contain both positively and negatively charged species on the same chain.[114] Antifouling properties of the zwitterionic polymer were originated by hydration shell (via electrostatic interactions), which is much stronger than hydrogen bonds, resulting in denser and tighter adsorbed water.[115] The most commonly used cationic group is a quaternary ammonium, while the anionic group may be a carboxylate, sulfonate or phosphate.

However, zwitterionic monomers commercialization is limited for their expensive price and pseudo-zwitterionic (co)polymers, mixture of positively and negatively charged monomer subunits, were proposed as alternative antifouling materials. George M. Whitesides and co-workers [116] were the first group demonstrating the similar properties of these compounds, resisting the absorption of proteins on self-assembled monolayers attached on gold substrates. After that, high number of articles were published providing the non-fouling properties of pseudo-zwitterionic compounds, synthesised for example, via plasma-induced surface grafting,[117] atom transfer radical polymerisation[118] and self-assembled monolayers[119] methods.

Covalently attached monolayers may be prepared mainly by three systems: "grafting from", "grafting to" and "grafting through" (Figure 1.16).

1.5.1. *"Grafting to"*

In grafting to approach, (end-)functionalised polymers react chemically with complementary reactive groups on the substrate surface.[120] The synthesis of functionalised polymer can be carried out via either free radical polymerisation or controlled/living radical polymerisation. Related to chemical point of view, grafting to system is less challenging than other grafting techniques due to elaborate synthetic procedures are not needed. Likewise, this technique allows characterising reactive (co)polymers prior immobilisation by chemical and physical methods, synthesising polymers with a narrow molecular weight distribution, therefore obtaining well-defined brushes. Nevertheless, the number of functional groups per surface area (grafting density) can be limited kinetically and thermodynamically. The kinetics of the adsorption process slow down when the surface is partially covered, because the reactive spots of the surface are filled. Moreover, reactive (co)polymers will find steric repulsion by the chains already placed. For these reasons, film thicknesses obtained via grafting to approach in dry conditions usually are lower than 5 nm, although thickness could increase significantly in wet conditions.[121, 122]

1.5.2. "Grafting from"

In "grafting from" strategy, also known as surface initiated polymerisation (SIP), the monomers polymerise at the surface of substrates using fractions of surface attached initiators. Firstly, the initiator is immobilised at the surface and then, with addition of monomer, the (co)polymers chains grow from this initiator. "Grafting from" approach presents two main limiting factors on the polymerisation: the troubles to immobilise the initiator on the surface of the substrate and the monomer diffusion on the dissolution. If we compare "grafting from" and "grafting to" approaches, usually denser layers are produced using the first strategy. The monomer is smaller than polymer and because of that its not experienced kinetic diffusion limitations.[44]
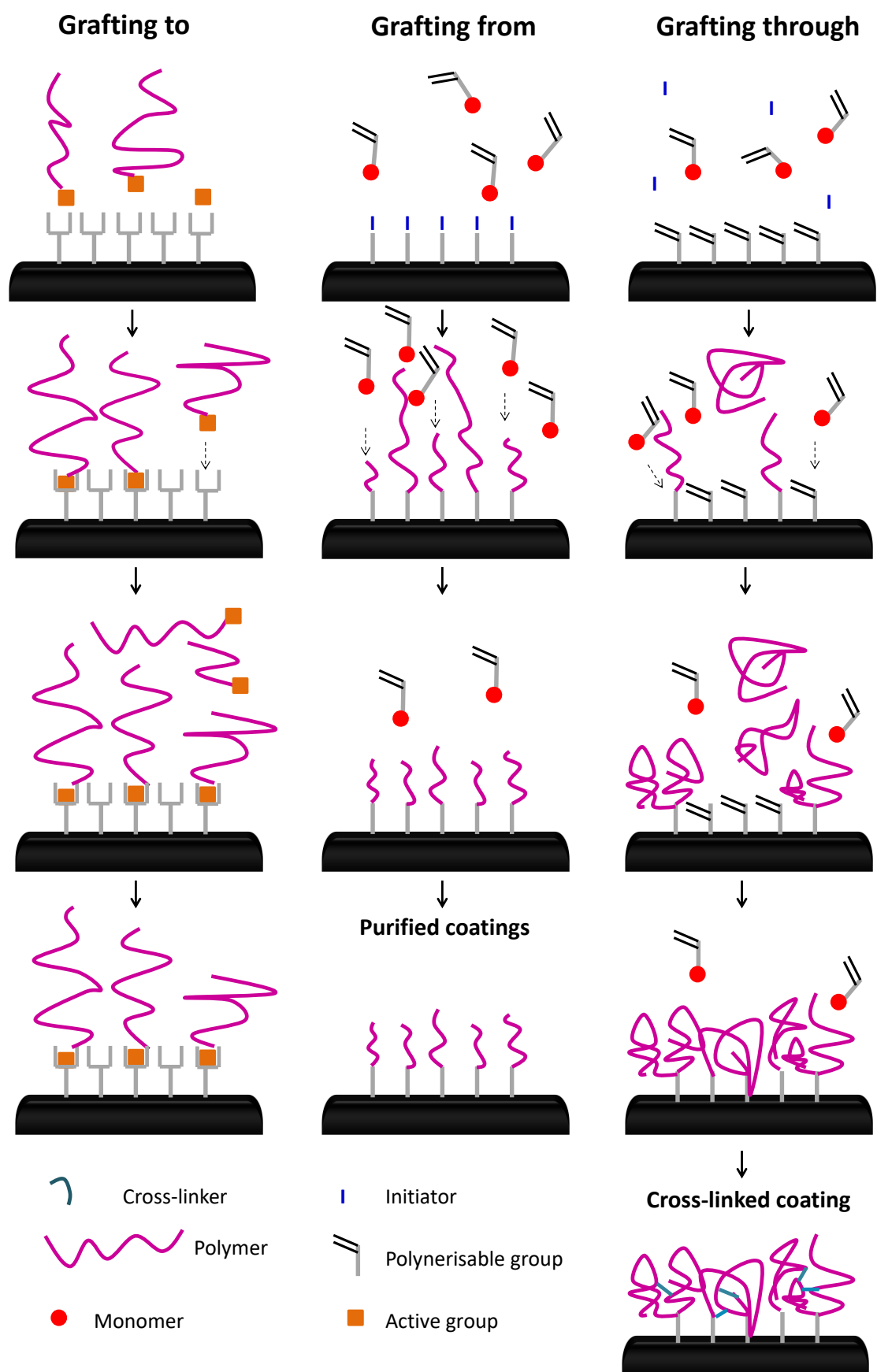
Figure 1.16. Schematic representation of "grafting to", "grafting from" and "granting through" approaches.

1.5.3. *"Grafting through"*

"Grafting through", or macromonomer method, can be considered as an intermediate technique between "grafting to" and "grafting from" strategies, because part of the polymerisation is performed in solution in the presence of functionalised surface that can react during the polymerisation.[123]

The growth of the polymer chain is initiated in solution by initiator. During propagation, some of the monomer bounded to the surface can be integrated into the growing chains, anchoring directly the polymer chains. The attached molecule can continue growing from the surface by reacting with added monomer units.

So far, this technique is the less studied from a scientific point of view, and for this reason, the mechanisms that are involved are not completely clear.[44]. The coatings generated via "grafting through" method are polymerised in-situ, to generate random conformation of the polymer network. This improves the swelling capacity of the coatings compared to the coatings based on cross-linked gel brushes in which the thickness of the swollen coating is restricted to the lengths of the polymers chains.[124, 125] Besides, from a production point of view, "grafting through" approach is easier than "grafting from" technique and the chain densities obtained are higher than when using "grafting to" method.

It is known that hydrogels and other soft, wet and dynamic surfaces synthesised by different techniques are widely used in biomedical applications to decrease the attachment of biologic microorganisms.[126] However, those hydrogels present low mechanical properties after water absorption[127, 128] making harder their use on ships technologies. Moreover, to apply those on ships surfaces or aquaculture networks seem almost impossible.

In order to decrease and prevent the formation of biofouling, wide variation of coatings were developed and tested in the marine sector. For many years, Tributyltin (TBT) was used as a main biocide in antifouling coatings industry. Nevertheless, in 2008, the use of TBT on vessels was banned,[125] due to several deformities on shellfishes and the bioaccumulation of tin in some ducks, seals and fishes were

observed.[129, 130] After that, copper and their derivatives were started to be used as alternative biocide. However, nowadays the use of copper in antifouling paints is also creating some controversy.[131] Moreover, most of the marine anti-fouling systems that are available in the market are organic paints that create high level of volatile organic chemicals (VOCs). In order to remove metal based biocides and organic solvents from marine environment, more environmentally friendly approaches such as, surfaces with different topographies,[132, 133] polymeric elastomers with a low surface energy,[134] enzymes[135] or application of pulse electrical field[136] were developed and tested at lab scale in the last two decades. Yet, most of the those new alternatives are useless in real applications mainly because of their elevated price or low applicability.[137]

General Objectives

1. Synthesise zwitterionic and pseudo-zwitterionic ultrathin hydrogels via grafting through method, and demonstrate their properties as protein resistance coatings.

2. To stablish the reaction conditions that will enable the synthesis of well-defined polymers by RAFT polymerisation to be used as emulsifiers on the synthesis of waterborne nanoparticles. These polymers will be used as macro-CTAs and will be based on polymers with antifouling properties. For that purpose, our objective will consist on the synthesis of well-defined polymers based on zwitterionic monomers, polyethylene glycol methyl metyhacrylate, and copolymers containing a balanced amount of negatively charged and positively charged monomers (poly-pseudozwitterionic polymers).

3. To stablish the reaction conditions to obtain well defined stable film forming waterborne nanoparticles coated with polyzwitterionic and pseudo-zwitterionic macro-CTAs.

4. To demonstrate dual functionality of those macro-CTAs improving the stability of the particles in dispersion, and preventing protein adsorption when forming films.

5. To demonstrate scalability of the particles and functionality on relevant marine conditions.

6. To stablish the reaction conditions to obtain well defined stable hard waterborne nanoparticles coated with poly(polyethylene glycol methyl metyhacrylate) macro-CTAs.

7. To study the cytotoxicity polystyrene particles for biomedical applications.

References

1.   S. G. Mokrushin, *Nature*, 1962, **195**, 861.
2.   F. Tadros Tharwat, *Basic Principles of Interface Science and Colloid Stability. Gruyter Reference. Germany*. *2017.*
3.   C. A. Finch, *Polymer International*, 1998, **47**, 85-85.
4.   US patent 1864078; Farbenindustrie A.G. (1932).
5.   US patent 1732795, Goodyear Tire & Rubber Co (1929).
6.   US patent 1860681; Farbenindustrie A.G. (1932).
7.   M. H. Ulrich, *Chemical Engineering & Technology*, 1989, **12**, 71-87.
8.   H. Warson, *Polymer International*, 1996, **41**, 352-352.
9.   M. F. Kemmere, *Batch Emulsion Polymerization: A Chemical Engineering Approach. Technische Universiteit Eindhoven. Netherland*, Technische Universiteit Eindhoven. *1999.*
10.   D. Sudol, *Polymeric Dispersions: Principles and Applications. Kluwer Academic. Dordrech, 1997.*
11.   P. A. Lovell and M. S. El-Aasser, *Emulsion Polymerization and Emulsion Polymers. John Wiley and Sons. Manchester*. *1997.*
12.   H. W. a. C. A. Finch, *Applications of synthetic resin latices: Volume 1, Fundamental chemistry of latices and application in adhesives.*, 2005.
13.   D. Urban and K. Takamura, *Polymer dispersions and their industrial applications*, Wiley-VCH, 2002.
14.   C.-S. Chern, in *Principles and Applications of Emulsion Polymerization. 2008. John Wiley & Sons. New Jersey.* , ed. J. W. Sons, 2008.
15.   K. Matyjaszewski, in *Advances in Controlled/Living Radical Polymerization*, American Chemical Society, 2003.
16.   D. Dupin, Preparation, Characterisation and Applications of Poly(2-vinylpyridine) Latex/Microgel,Thesis, The University Of Sheffield, Sheffield, United Kingdom, 2007.
17.   C. S. Chern, *Progress in Polymer Science*, 2006, **31**, 443-486.
18.   A. K. Khan, B. C. Roy and S. Dolui, *Journal of Scientific and Industrial Research*, 2006, **65**, 744-746.
19.   L. Liu and W. Yang, *Journal of Polymer Science Part A*, 2004, **42**, 846-852.
20.   M. E. Thomson, A.-M. Manley, J. S. Ness, S. C. Schmidt and M. F. Cunningham, *Macromolecules*, 2010, **43**, 7958-7963.
21.   W. V. Smith and R. H. Ewart, *The Journal of Chemical Physics*, 1948, **16**, 592-599.
22.   R. G. W. Norrish and R. R. Smith, *Nature*, 1942, **150**, 336-337.
23.   E. Trommsdorff, H. Kohle and P. Lagally, *Makromolekulare Chemie*, 1948, **1**, 169-198.
24.   A. El-hoshoudy, *Emulsion Polymerization Mechanism. 2018. Nevin Cankaya. Zagreb*, 2018.
25.   J. Verran and R. D. Boyd, *Biofouling*, 2001, **17**, 59-71.
26.   L. B. and B. B. W., *Polymer International*, 1992, **29**, 41-46.
27.   G. W. Poehlein and D. J. Dougherty, *Rubber Chemistry and Technology*, 1977, **50**, 601-638.
28.   R. J. Hunter, *Foundations of colloid science. 2001. Oxford University Press. United Kingdom*, 2001.
29.   P. Attard, *Current Opinion in Colloid & Interface Science*, 2001, **6**, 366-371.
30.   D. Wang, *Angewandte Chemie International Edition*, 2006, **45**, 2498-2498.
31.   L. Leemans, R. Fayt, P. Teyssie and N. C. De Jaeger, *Macromolecules*, 1991, **24**, 5922-5925.
32.   K. B.Singh, Understanding film formation mechanism in latex dispersions, Thesis, Indian Institute of technology Bombay, Mumabu, India, 2008.

33. M. A. Winnik, *Curr. Opin. Colloid Interface Sci.*, 1997, **2**, 192-199.
34. E. Aramendia, M. J. Barandiaran, J. Grade, T. Blease and J. M. Asua, *Langmuir*, 2005, **21**, 1428-1435.
35. M. Szwarc, *Nature* 1956, **178**, 1168-1169.
36. M. Szwarc, M. Levy and R. Milkovich, *Journal of the American Chemical Society*, 1956, **78**, 2656-2657.
37. O. W. Webster, *Science* 1991, **251**, 887-893.
38. K. Matyjaszewski, *Progress in Polymer Science*, 2005, **30**, 858-875.
39. J. M. J. Frechet, *Progress in Polymer Science*, 2005, **30**, 844-857.
40. K. Matyjaszewski, in *Controlled Radical Polymerization*, American Chemical Society, 1998.
41. K. Matyjaszewski, in *Advances in Controlled/Living Radical Polymerization*, American Chemical Society, 2003.
42. W.A. Braunecker and K. Matyjaszewski, *Progress in Polymer Science*, 2007, **32**, 93-146.
43. P. B. Zetterlund, *Polymer Chemistry*, 2011, **2**, 534-549.
44. E. Lizundia, E. Meaurio and J. L. Vilas, in *Multifunctional Polymeric Nanocomposites Based on Cellulosic Reinforcements. William Andrew Publishing. United States*, *2016.*
45. X. Zhu, D. Jańczewski, S. S. C. Lee, S. L.-M. Teo and G. J. Vancso, *ACS Applied Materials & Interfaces*, 2013, **5**, 5961-5968.
46. J. O'Donnell, *Journal of the American Chemical Society*, 2010, **132**, 10206-10207.
47. M. K. Georges, R. P. N. Veregin, P. M. Kazmaier and G. K. Hamer, *Macromolecules*, 1993, **26**, 2987-2988.
48. L. Petton, A. E. Ciolino, B. Dervaux and F. E. Du Prez, *Polym. Chem.*, 2012, **3**, 1867-1878.
49. D. Benoit, V. Chaplinski, R. Braslau and C. J. Hawker, *Journal of the American Chemical Society*, 1999, **121**, 3904-3920.
50. A. Goto and T. Fukuda, *Progress in Polymer Science*, 2004, **29**, 329-385.
51. C. J. Hawker, A. W. Bosman and E. Harth, *Chemical Review*, 2001, **101**, 3661-3688.
52. M. Kato, M. Kamigaito, M. Sawamoto and T. Higashimura, *Macromolecules*, 1995, **28**, 1721-1723.
53. J.-S. Wang and K. Matyjaszewski, *Journal of the American Chemical Society*, 1995, **117**, 5614-5615.
54. A. Bianchi, Living radical polymerization for the preparation of innovative macromolecular architecture, Thesis, University of Milano, Milano, Italy, 2013.
55. J. Chiefari, Y. K. Chong, F. Ercole, J. Krstina, J. Jeffery, T. P. T. Le, R. T. A. Mayadunne, G. F. Meijs, C. L. Moad, G. Moad, E. Rizzardo and S. H. Thang, *Macromolecules*, 1998, **31**, 5559-5562.
56. D. J. Keddie, G. Moad, E. Rizzardo and S. H. Thang, *Macromolecules*, 2012, **45**, 5321-5342.
57. D. B. Thomas, A. J. Convertine, L. J. Myrick, C. W. Scales, A. E. Smith, A. B. Lowe, Y. A. Vasilieva, N. Ayres and C. L. McCormick, *Macromolecules*, 2004, **37**, 8941-8950.
58. Y. Yuan and T. R. Lee, in *Surface Science Techniques. Springer Berlin Heidelberg. Berlin*, *2013.*
59. A. M. C. Pereira, Synthesis of anisotropic polymer / inorganic composite particles via RAFT-mediated emulsion polymerization, Thesis, L'Universite Claude Bernard Lyon I, Lyon, France, 2014.
60. K. Matyjaszewski, in *Controlled/Living Radical Polymerization*, American Chemical Society, 1995, **117**, 5614-5615.
61. C. Barner-Kowollik, *Handbook of RAFT Polymerization. Wiley. Weinheim*, *2008.*
62. I. Fitridge, T. Dempster, J. Guenther and N. R. de, *Biofouling*, 2012, **28**, 649-669.
63. B. Charleux, G. Delaittre, J. Rieger and F. D'Agosto, *Macromolecules*, 2012, **45**, 6753-6765.
64. I. B. Beech, *International Biodeterioration & Biodegradation*, 2004, **53**, 177-183.

65.   A. v. Herk, *Chemistry and Technology of Emulsion Polymerisation. Blackwell Publishin. United States*, *2005.*

66.   P. Taylor, *Advances in Colloid and Interface Science*, 1998, **75**, 107-163.

67.   C. D. Anderson and E. S. Daniels, *Emulsion Polymerisation and Latex Applications*, Rapra Technology, 2003.

68.   P. B. Zetterlund, S. C. Thickett, S. Perrier, E. Bourgeat-Lami and M. Lansalot, *Chemical Review*, 2015, **115**, 9745-9800.

69.   J. P. Russum, C. W. Jones and F. J. Schork, *Macromolecular Rapid Communications*, 2004, **25**, 1064-1068.

70.   J. M. Asua, *Progress in Polymer Science*, 2014, **39**, 1797-1826.

71.   S. E. Shim, H. Jung, H. Lee, J. Biswas and S. Choe, *Polymer*, 2003, **44**, 5563-5572.

72.   P. J. Saikia, J. M. Lee, B. H. Lee and S. Choe, *Radical polymerisation,* 2007, **249**, 249-258.

73.   F. Huo, X. Wang, Y. Zhang, X. Zhang, J. Xu and W. Zhang, *Macromolecular Chemistry and Physics*, 2013, **214**, 902-911.

74.   J. Tan, X. Rao, X. Wu, H. Deng, J. Yang and Z. Zeng, *Macromolecules* 2012, **45**, 8790-8795.

75.   J. Tan, X. Rao, J. Yang and Z. Zeng, *Macromolecules* 2013, **46**, 8441-8448.

76.   Y. Li and S. P. Armes, *Angewandte Chemie International Edition* 2010, **49**, 4042-4046.

77.   E. R. Jones, M. Semsarilar, A. Blanazs and S. P. Armes, *Macromolecules*, 2012, **45**, 5091-5098.

78.   D. Zehm, L. P. D. Ratcliffe and S. P. Armes, *Macromolecules*, 2013, **46**, 128-139.

79.   L. A. Fielding, M. J. Derry, V. Ladmiral, J. Rosselgong, A. M. Rodrigues, L. P. D. Ratcliffe, S. Sugihara and S. P. Armes, *Chemical Science*, 2013, **4**, 2081-2087.

80.   L. P. D. Ratcliffe, B. E. McKenzie, G. M. D. Le Bouedec, C. N. Williams, S. L. Brown and S. P. Armes, *Macromolecules* 2015, **48**, 8594-8607.

81.   A. Blanazs, J. Madsen, G. Battaglia, A. J. Ryan and S. P. Armes, *Journal of the American Chemical Society*, 2011, **133**, 16581-16587.

82.   P. Yang, L. P. D. Ratcliffe and S. P. Armes, *Macromolecules* 2013, **46**, 8545-8556.

83.   Q. Shen, L. Liu and W. Zhang, *Langmuir*, 2014, **30**, 9361-9369.

84.   W.-M. Wan and C.-Y. Pan, *Macromolecules* 2010, **43**, 2672-2675.

85.   W.-M. Wan and C.-Y. Pan, *Polymer Chemistry*, 2010, **1**, 1475-1484.

86.   S. W. Prescott, M. J. Ballard, E. Rizzardo and R. G. Gilbert, *Macromolecules*, 2005, **38**, 4901-4912.

87.   M. J. Monteiro, M. Hodgson and H. De Brouwer, *Journal of Polymer Science Part A: Polymer Chemistry*, 2000, **38**, 3864-3874.

88.   S. W. Prescott, M. J. Ballard, E. Rizzardo and R. G. Gilbert, *Macromolecules*, 2002, **35**, 5417-5425.

89.   C. J. Ferguson, R. J. Hughes, B. T. T. Pham, B. S. Hawkett, R. G. Gilbert, A. K. Serelis and C. H. Such, *Macromolecules*, 2002, **35**, 9243-9245.

90.   S. Nozari and K. Tauer, *Polymer*, 2005, **46**, 1033-1043.

91.   S. Nozari, K. Tauer and A. M. I. Ali, *Macromolecules*, 2005, **38**, 10449-10454.

92.   Y. Luo and X. Cui, *Journal of Polymer Science Part A: Polymer Chemistry*, 2006, **44**, 2837-2847.

93.   R. G. Gilbert, *Macromolecules*, 2006, **39**, 4256-4258.

94.   S. Freal-Saison, M. Save, C. Bui, B. Charleux and S. Magnet, *Macromolecules*, 2006, **39**, 8632-8638.

95.   C. J. Ferguson, R. J. Hughes, D. Nguyen, B. T. T. Pham, R. G. Gilbert, A. K. Serelis, C. H. Such and B. S. Hawkett, *Macromolecules*, 2005, **38**, 2191-2204.

96.   M. Manguian, M. Save and B. Charleux, *Macromolecular Rapid Communications*, 2006, **27**, 399-404.

97.   C. Isabelle, Z. Wenjing, R. Jutta, L. Muriel, D. A. Franck and C. Bernadette, *Macromolecular Rapid Communications*, 2011, **32**, 1270-1276.
98.   W. Zhang, F. D'Agosto, O. Boyron, J. Rieger and B. Charleux, *Macromolecules*, 2011, **44**, 7584-7593.
99.   I. Chaduc, A. Crepet, O. Boyron, B. Charleux, F. D'Agosto and M. Lansalot, *Macromolecules* 2013, **46**, 6013-6023.
100.   J. Lesage de la Haye, X. Zhang, I. Chaduc, F. Brunel, M. Lansalot and F. D'Agosto, *Angewandte Chemie International Edition* 2016, **55**, 3739-3743.
101.   E. Velasquez, J. Rieger, F. Stoffelbach, B. Charleux, F. D'Agosto, M. Lansalot, P.-E. Dufils and J. Vinas, *Polymer*, 2013, **54**, 6547-6554.
102.   S. Boisse, J. Rieger, K. Belal, A. Di-Cicco, P. Beaunier, M.-H. Li and B. Charleux, *Chemical Communications*, 2010, **46**, 1950-1952.
103.   S. Boisse, J. Rieger, G. Pembouong, P. Beaunier and B. Charleux, *Journal of Polymer Science Part A: Polymer Chemistry*, 2011, **49**, 3346-3354.
104.   N. J. Warren and S. P. Armes, *Journal of the American Chemical Society*, 2014, **136**, 10174-10185.
105.   S. Mona, J. E. R., B. Adam and A. S. P., *Advanced Materials*, 2012, **24**, 3378-3382.
106.   A. M. dos Santos, J. Pohn, M. Lansalot and F. D'Agosto, *Macromolecules Rapid Communication*, 2007, **28**, 1325-1332.
107.   E. Velasquez, J. Rieger, F. Stoffelbach, F. D'Agosto, M. Lansalot, P.-E. Dufils and J. Vinas, *Polymer*, 2016, **106**, 275-284.
108.   J. Lesage de la Haye, I. Martin-Fabiani, M. Schulz, J. L. Keddie, F. D'Agosto and M. Lansalot, *Macromolecules* 2017, **50**, 9315-9328.
109.   I. Martin-Fabiani, J. Lesage de la Haye, M. Schulz, Y. Liu, M. Lee, B. Duffy, F. D'Agosto, M. Lansalot and J. L. Keddie, *ACS Applied Materials & Interfaces*, 2018, **10**, 11221-11232.
110.   S. Nehache, C.-C. Yeh, M. Semsarilar, A. Deratani, Y. Chang and D. Quemener, *Macromolecular Bioscience*, 2016, **16**, 57-62.
111.   Z. Zhang, J. A. Finlay, L. Wang, Y. Gao, J. A. Callow, M. E. Callow and S. Jiang, *Langmuir*, 2009, **25**, 13516-13521.
112.   N. Aldred, G. Li, Y. Gao, A. S. Clare and S. Jiang, *Biofouling*, 2010, **26**, 673-683.
113.   Y. Ohara, K. Nakai, S. Ahmed, K. Matsumura, K. Ishihara and S.-i. Yusa, *Langmuir*, 2018, **35**, 1249-1256.
114.   S. Lowe, N. M. O'Brien-Simpson and L. A. Connal, *Polymer Chemistry*, 2015, **6**, 198-212.
115.   S. Chen, L. Li, C. Zhao and J. Zheng, *Polymer*, 2010, **51**, 5283-5293.
116.   R. E. Holmlin, X. Chen, R. G. Chapman, S. Takayama and G. M. Whitesides, *Langmuir*, 2001, **17**, 2841-2850.
117.   A. Venault, T.-C. Wei, H.-L. Shih, C.-C. Yeh, A. Chinnathambi, S. A. Alharbi, S. Carretier, P. Aimar, J.-Y. Lai and Y. Chang, *Journal of Membrane Science*, 2016, **516**, 13-25.
118.   L. Mi, M. T. Bernards, G. Cheng, Q. Yu and S. Jiang, *Biomaterials*, 2010, **31**, 2919-2925.
119.   M. Liao, G. Cheng and J. Zhou, *Journal of Physical Chemistry C*, 2017, **121**, 17390-17401.
120.   M. Welch, A. Rastogi and C. Ober, *Soft Matter*, 2011, **7**, 297-302.
121.   J. Ruhe and W. Knoll, *Journal of Macromolecular Science: Part C: Polymer Reviews*, 2002, **C42**, 91-138.
122.   T. Ekblad, Linköpings Universitet, Sweden, 2010.
123.   M. Bialk, O. Prucker and J. Ruhe, *Colloids Surface A*, 2002, **198-200**, 543-549.
124.   K. Ishihara, *Polymer Journal*, 2015, **47**, 585-597.
125.   C. Hellio and D. Yebra, in *Advances in Marine Antifouling Coatings and Technologies. 2009. Woodhead Publishing. United* Kingdom, 2009.
126.   N. A. Peppas, J. Z. Hilt, A. Khademhosseini and R. Langer, *Advanced Materials*, 2006, **18**, 1345-1360.

127.   T. R. Hoare and D. S. Kohane, *Polymer*, 2008, **49**, 1993-2007.

128.   M. Parlato, S. Reichert, N. Barney and W. L. Murphy, *Macromolecular bioscience*, 2014, **14**, 687-698.

129.   J. Strand and J. A. Jacobsen, *Science of the Total Environment*, 2005, **350**, 72-85.

130.   S. M. Evans, T. Leksono and P. D. McKinnell, *Marine Pollution Bulletin*, 1995, **30**, 14-21.

131.   N. Singh and A. Turner, *Marine Pollution Bulletin*, 2009, **58**, 559-564.

132.   A. J. Scardino, D. Hudleston, Z. Peng, N. A. Paul and N. R. de, *Biofouling*, 2009, **25**, 83-93.

133.   J. F. Schumacher, M. L. Carman, T. G. Estes, A. W. Feinberg, L. H. Wilson, M. E. Callow, J. A. Callow, J. A. Finlay and A. B. Brennan, *Biofouling*, 2007, **23**, 55-62.

134.   J. A. Callow, M. E. Callow, L. K. Ista, G. Lopez and M. K. Chaudhury, *Journal of the Royal Society Interface*, 2005, **2**, 319-325.

135.   N. Aldred, I. Y. Phang, S. L. Conlan, A. S. Clare and G. J. Vancso, *Biofouling*, 2008, **24**, 97-107.

136.   R. E. Perez-Roa, M. A. Anderson, D. Rittschof, B. Orihuela, D. Wendt, G. L. Kowalke and D. R. Noguera, *Biofouling*, 2008, **24**, 177-184.

137.   F. Hong, L. Xie, C. He, J. Liu, G. Zhang and C. Wu, *Polymer*, 2013, **54**, 2966-2972.
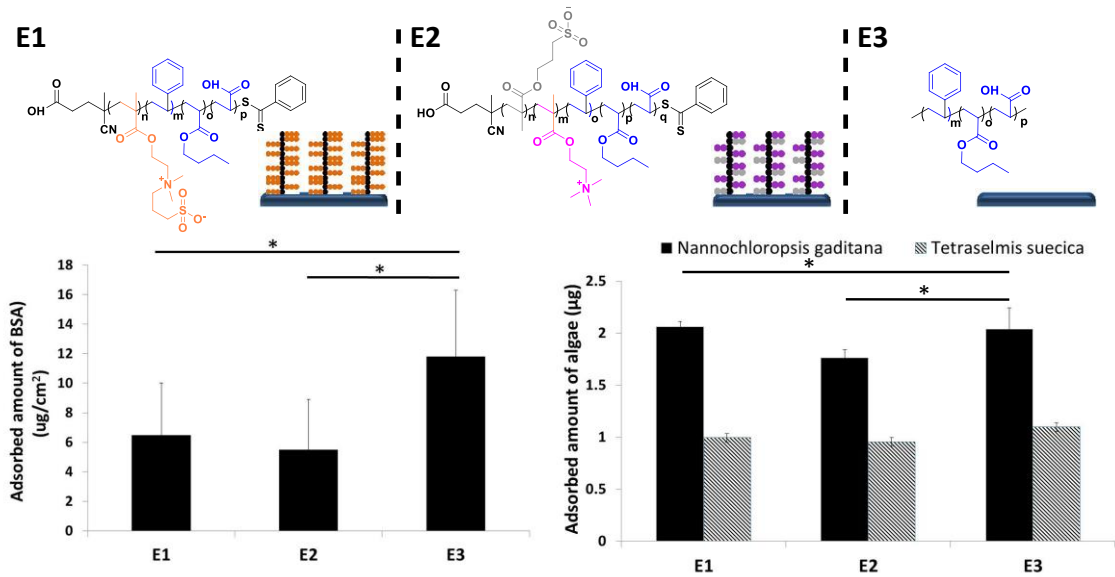
Chapter 2

Synthesis and characterisation of ultrathin poly(zwitterionic) and poly(pseudo-zwitterionic) coatings via "grafting through" approach
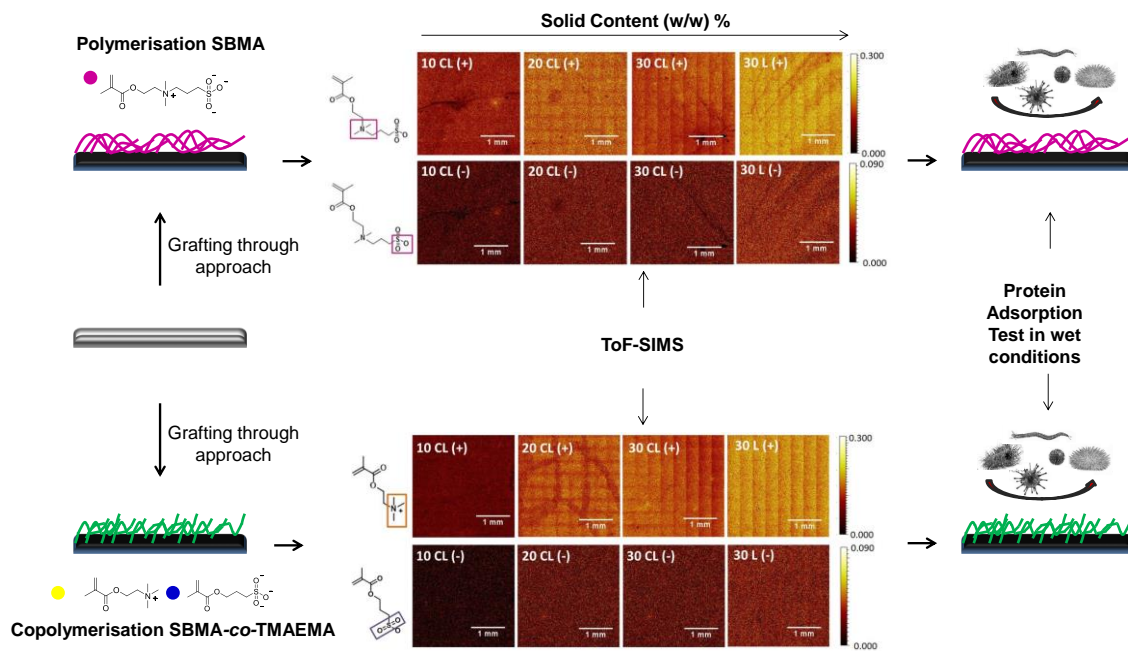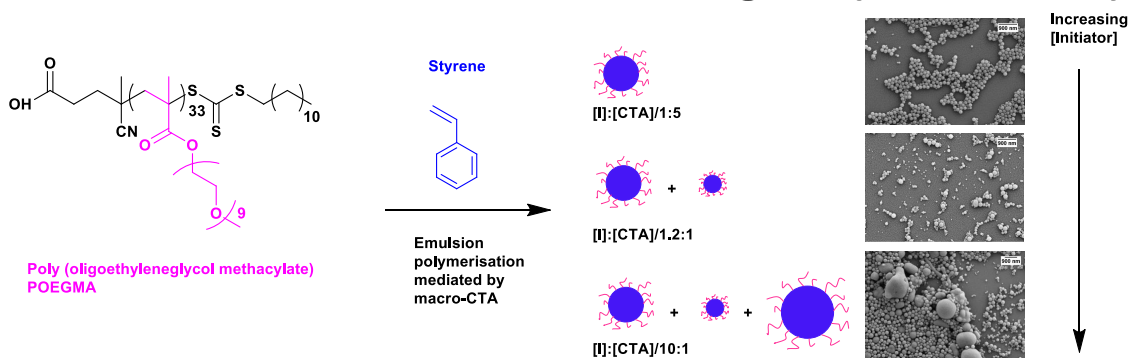
Chapter 3
Development and Characterisation of polymer latexes produced via aqueous emulsion polymerisation mediated by zwitterionic and pseudo-zwitterionic macro-CTAs

Chapter 4

Synthesis of biocompatible nanoparticles via aqueous emulsion polymerisation stabilised through poly(oligoethyleneglycol methacrylate) macromolecular chain transfer agent (macro-CTA)

Poly (oligoethyleneglycol methacylate)
POEGMA

Styrene

Emulsion polymerisation mediated by macro-CTA

[I]:[CTA]/1:5

[I]:[CTA]/1.2:1

[I]:[CTA]/10:1

Increasing [Initiator]

Chapter 5

General Conclusions and Future Works

Annexe I

Grafting to   **Grafting from**   **Grafting through**

Purified coatings

Cross-linked coating

⌐ Cross-linker	I Initiator
∿ Polymer	Polynerisable group
● Monomer	■ Active group
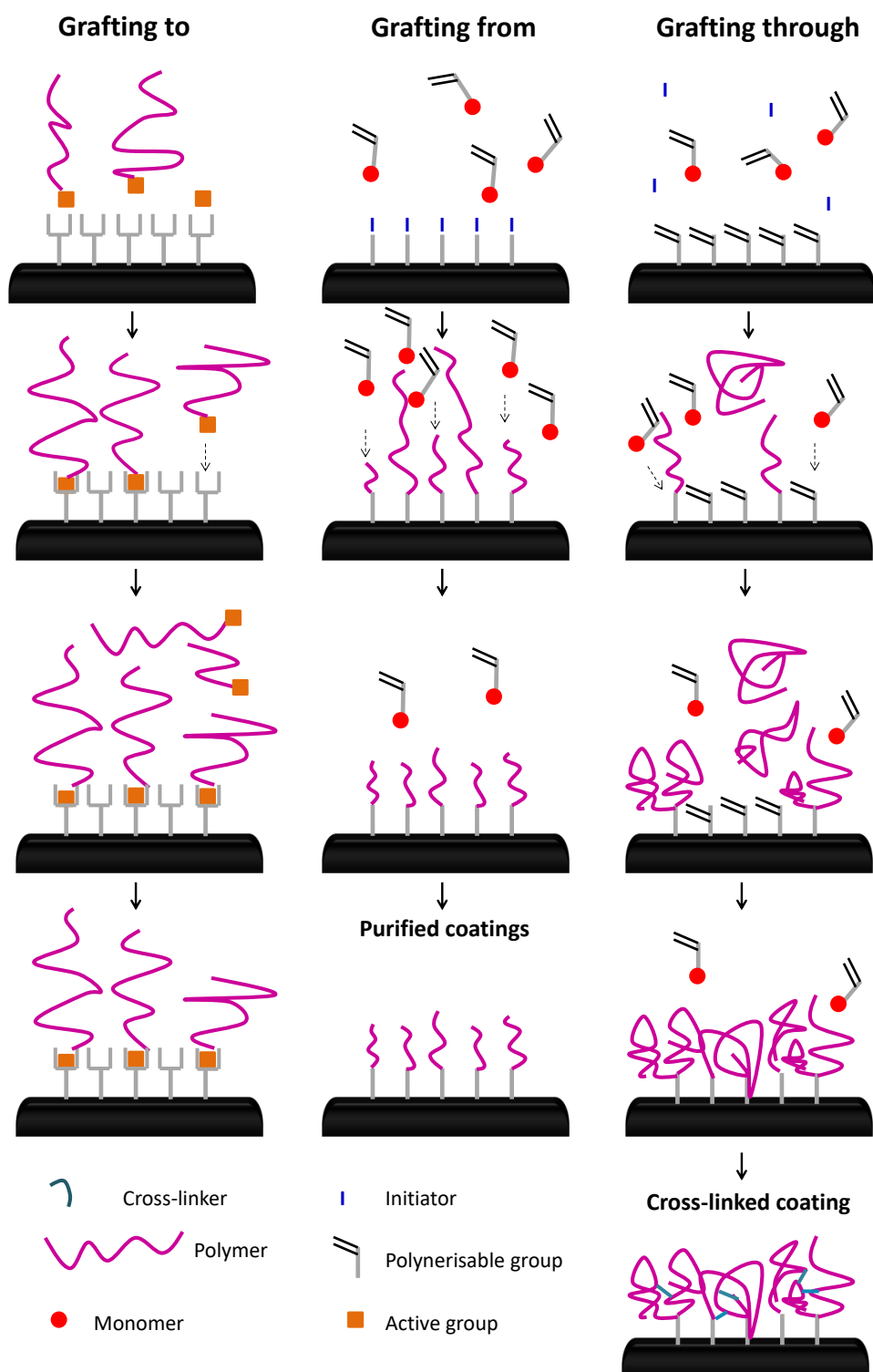
Figure AI.1. Schematic representation of "grafting to", "grafting from" and "grafting through" approaches to covalently immobilize onto surface.

Figure AI.2. Picture of "grafting through" sandwich method.
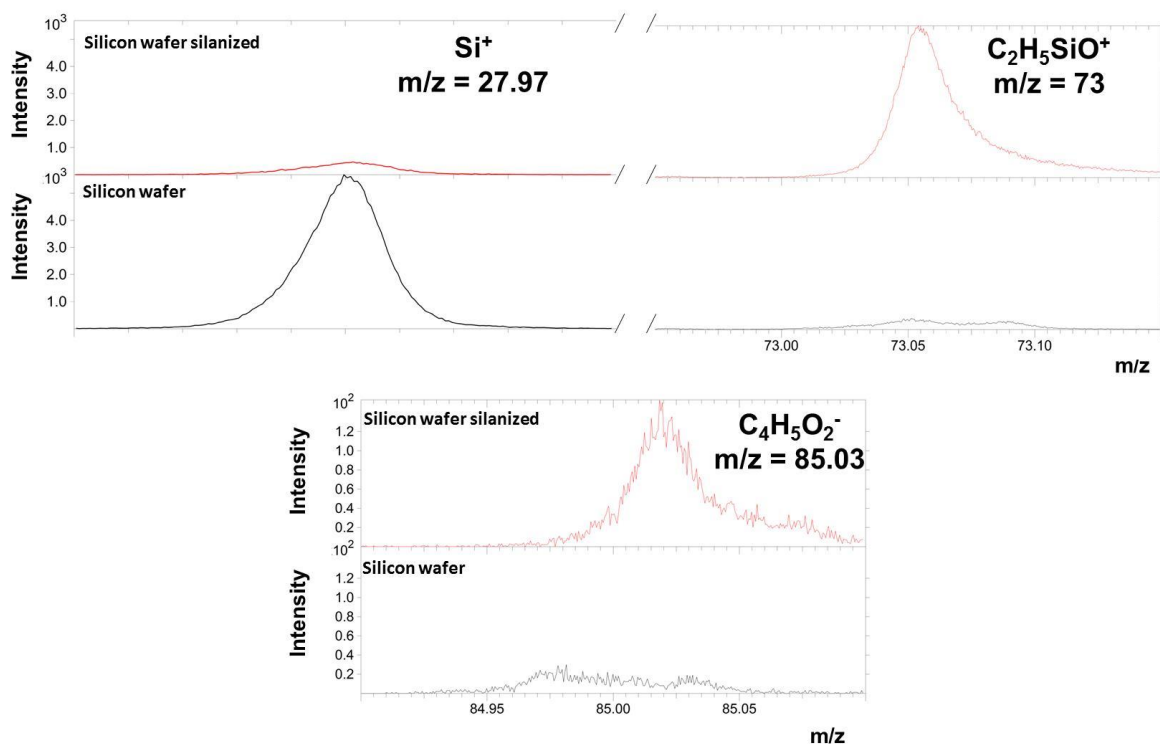
Figure AI.3. Magnified TOF-SIMS spectra of silanized and pristine silicon wafers. A) Positive ions (Si^+ and $C_2H_5SiO^+$). B) Negative ion ($C_4H_5O_2^-$).
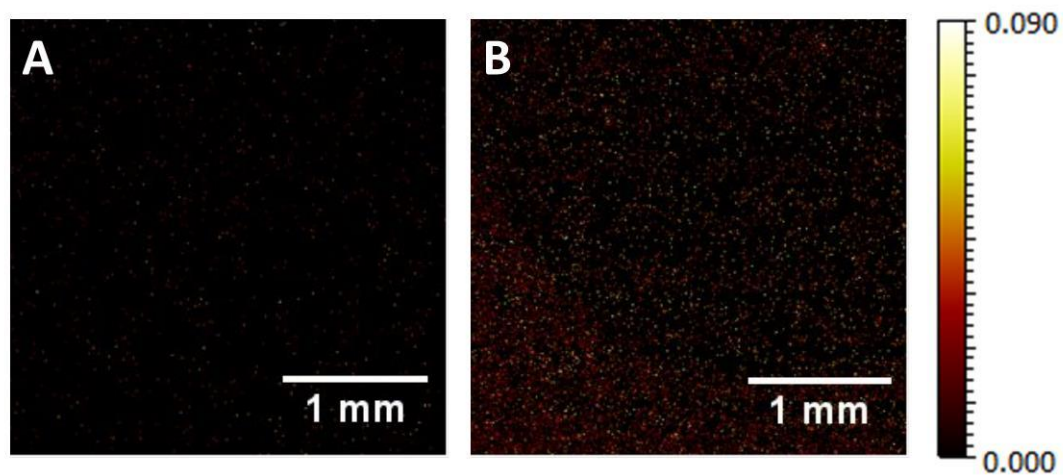
Figure AI.4. ToF-SIMS secondary ion images generated from the diagnostic of the negative ions of the surface (9 mm^2 analysed surface area). A) Silicon wafer ToF-SIMS imaging of the surface showing the secondary ion image generated from the diagnostic of $C_4H_5O_2^-$ anion. D) Silanised silicon wafer ToF-SIMS imaging of the surface showing the secondary ion image generated from the diagnostic of $C_4H_5O_2^-$ anion.
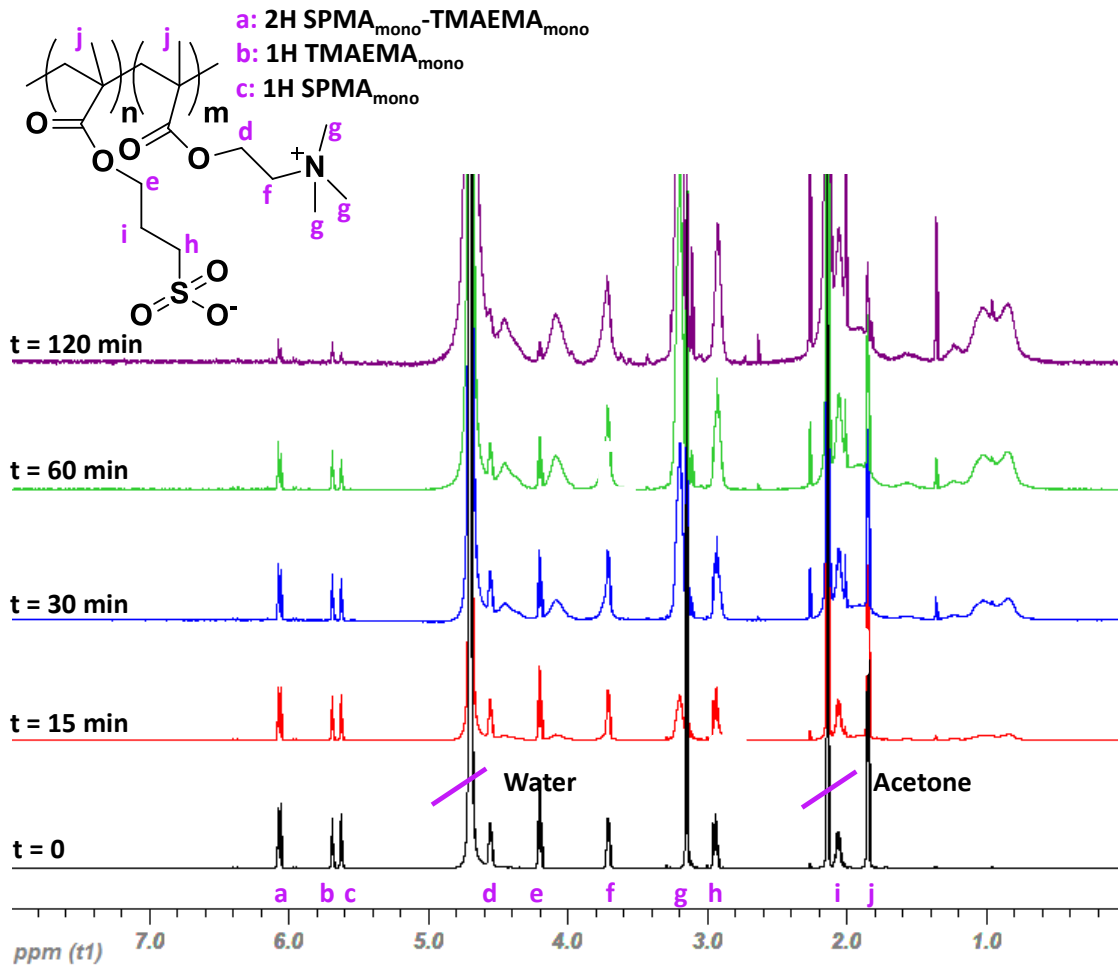
Figure AI.5. ^{1}H NMR spectra of P(SPMA)-co-(TMAEMA) bulk copolymerisation at differerent reaction time (t = 0, 15, 30, 60 and 120 min).
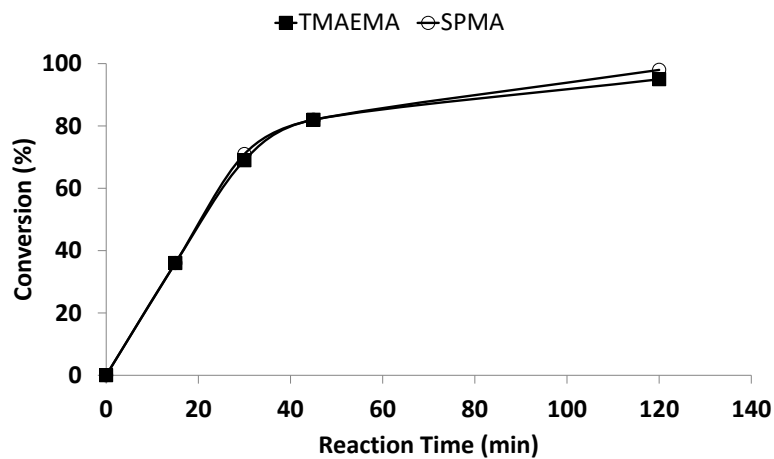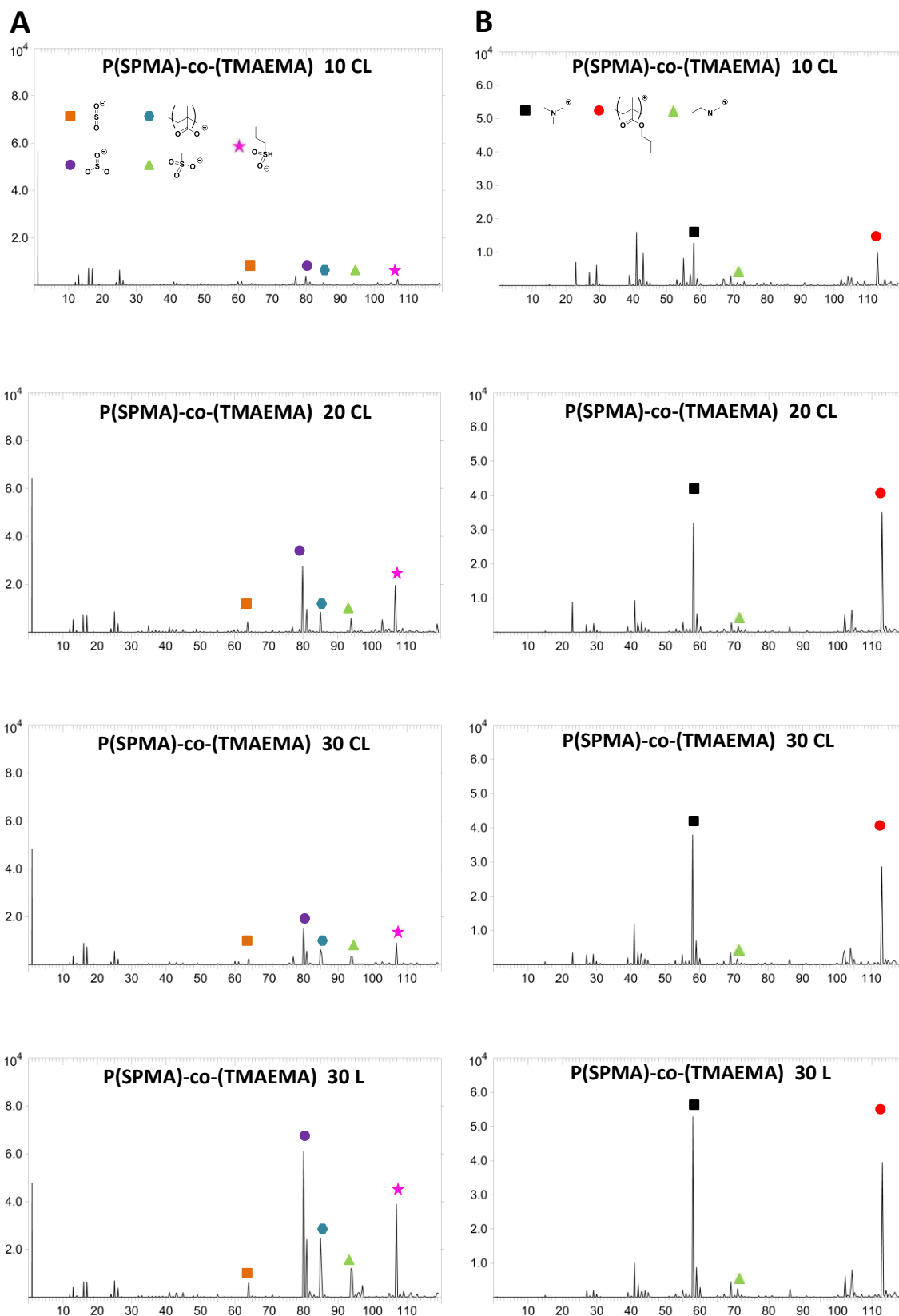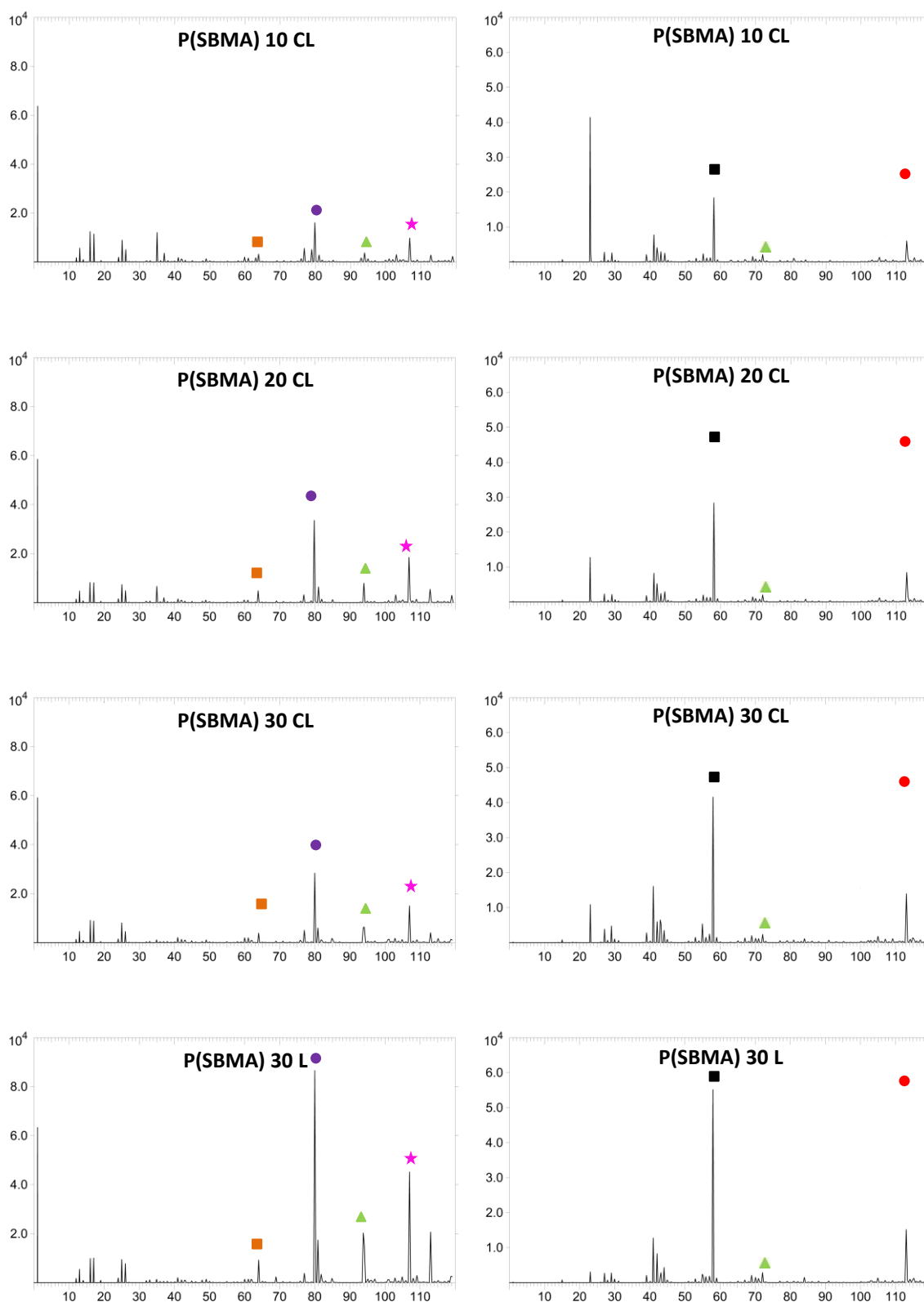

Figure AI.6. Reactions kinetics studies of P(SPMA)-co(TMAEMA) bulk copolymerisation at 30 wt%. The evolution of (co)monomers conversion as a function of time was determined by ^{1}H NMR
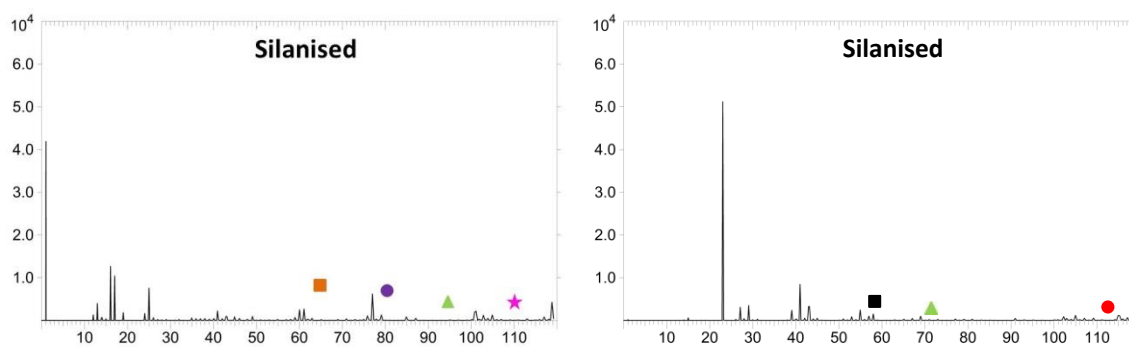
A

P(SPMA)-co-(TMAEMA) 10 CL

P(SPMA)-co-(TMAEMA) 20 CL

P(SPMA)-co-(TMAEMA) 30 CL

P(SPMA)-co-(TMAEMA) 30 L

B

P(SPMA)-co-(TMAEMA) 10 CL

P(SPMA)-co-(TMAEMA) 20 CL

P(SPMA)-co-(TMAEMA) 30 CL

P(SPMA)-co-(TMAEMA) 30 L

183

Figure AI.7. The negative (A) and positive (B) secondary ion ToF-SIMS mass spectrum of polymerised and sinalised glass slides surfaces.
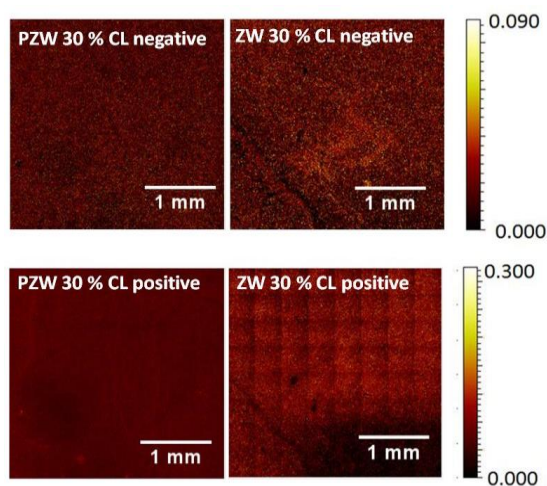

Figure AI.8. (co)Polymerised surfaces analysis by ToF-SIMS. ToF-SIMS imaging (3 x 3 mm^2 area, 304 x 304 pixels). ZW:[2-(methacryloyloxy)ethyl]dimethyl-(3-sulfopropyl)ammonium hydroxide polymers, PZW [(3-Sulfopropyl methacrylate) -co-[2(Methacryloyloxy)ethyl]trimethylammonium] Copolymers. CL: Cross-Linked surfaces with Tetra(ethylene glycol) diacrylate; 30: Amount of solid content in wt%; (-) SO$_2^-$ (-, m/z 64) used as fragmentation reference (+) C$_3$H$_8$N$^+$ (+, m/z 58) used as fragmentation reference.
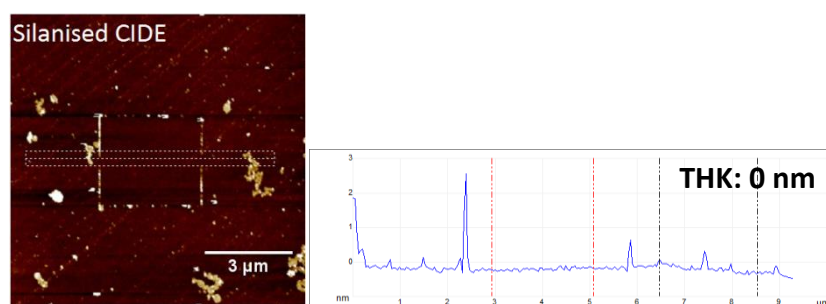
Figure AI.9. Tapping mode AFM 2D height image in air and step profile to measure the thickness of silanised coating.

Table AI.1. Summary of the conversion and molecular weights of pSMBA and p[(SPMA)-co-(TMAEMA)] linear (co)polymers.

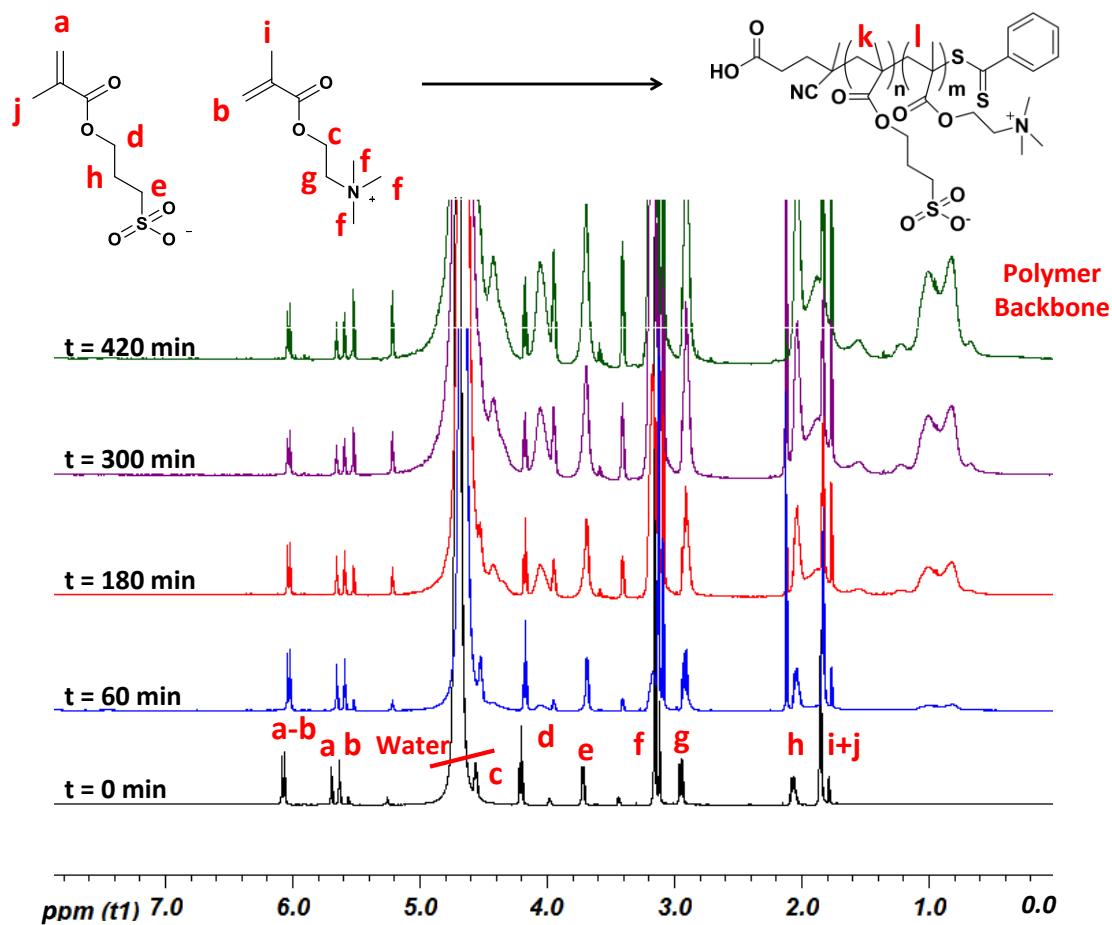| Polymer brushes	Conversion (%)	Mn (Da)	Mn/Mw
p[(SPMA)-co-(TMAEMA)]	98	55,400	3.2
pSMBA	98	83,800	2.8

Annexe II

Figure AII.1. Kinetics studies of P(SPMA)$_{98}$-co-(TMAEMA)$_{80}$ macro-CTA polymerisation monitories with ^{1}H NMR in D$_2$O.

.
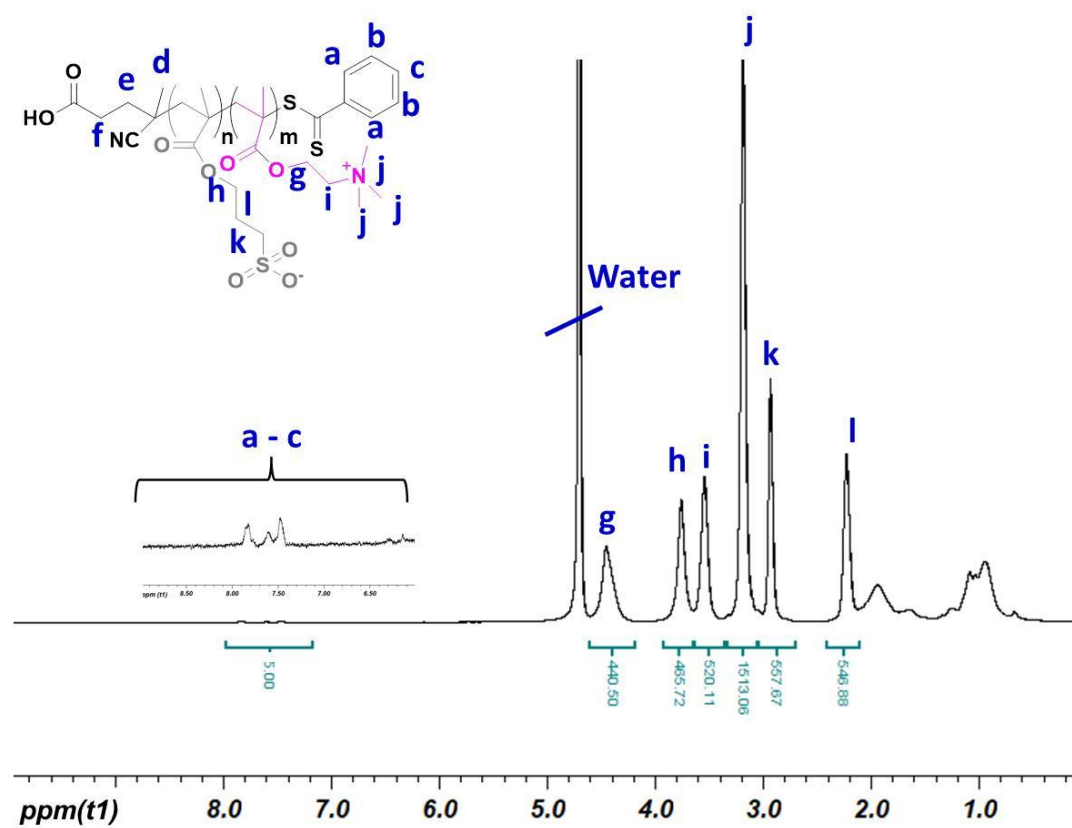
Figure AII.2. H NMR spectrum recorded for P(SPMA)$_{98}$-co-(TMAEMA)$_{80}$ macro-CTA in D$_2$O.

Nº	macro-CTA %
1.1	5,62
1.2	5.79
1.3	5.84
1.4	6.06
1.5	6.06
1.6	5.53
1.7	5.48
1.8	5.86
1.9	5.78
1.1	5.84
X	5.79
σ	0.18
Error %	3.20

Figure AII.3. Thermogravimetric analyses reproducibility studies of Y2-ACVA-P(SBMA) Y2-ACVA-P(SBMA) sample.

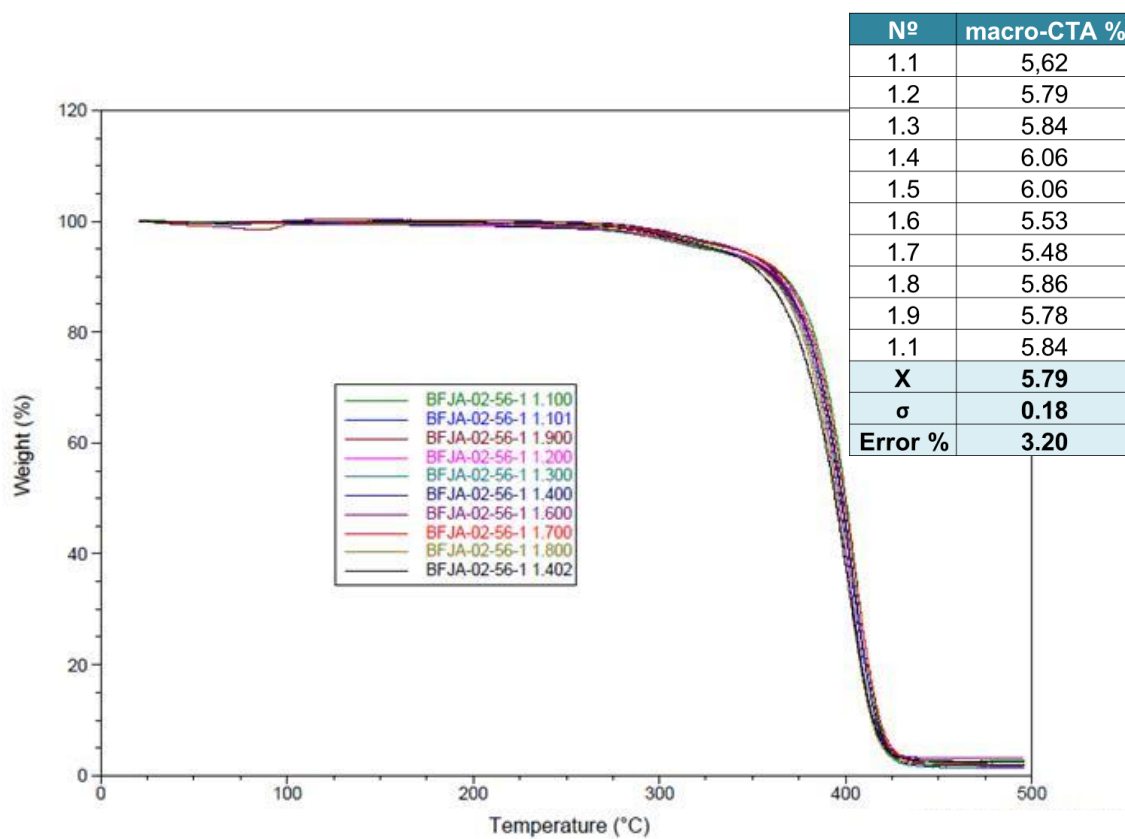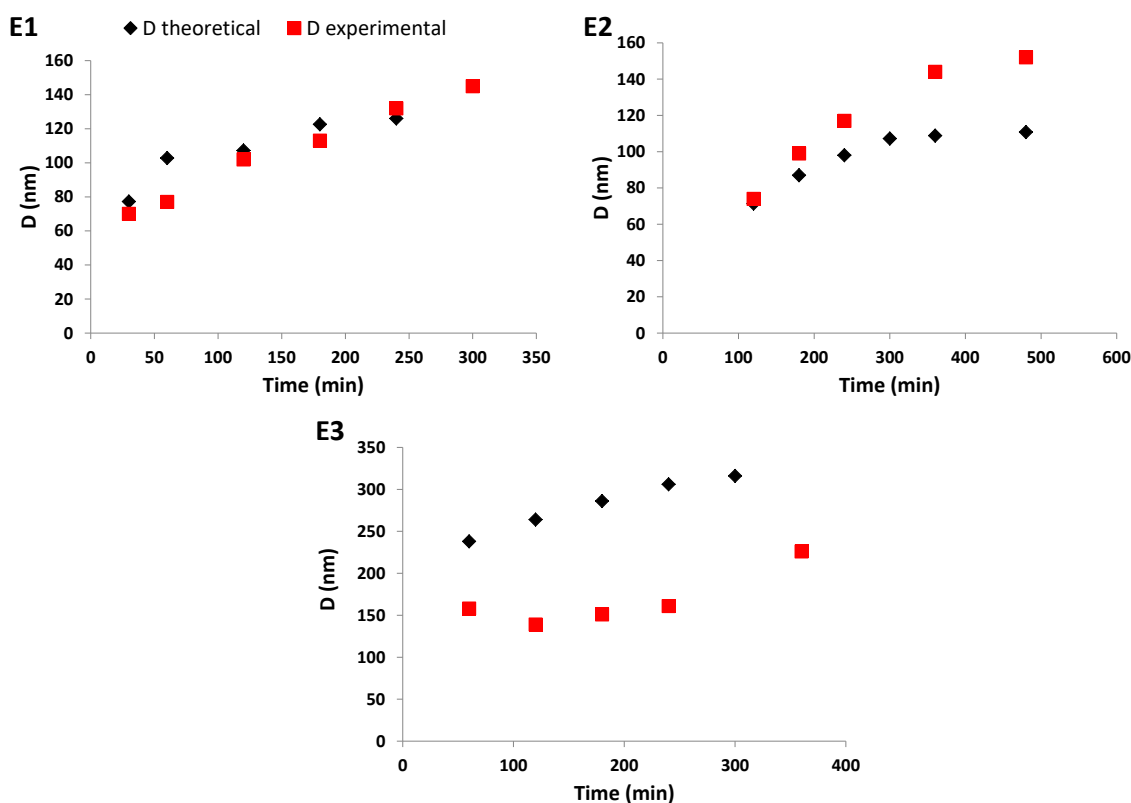**Figure AII.4** Theoretical and experimental Dh evolution as a function of reaction time. P(SBMA)$_{248}$ macro-CTA (E1) P[(SPMA)$_{78}$-co-(TMAEMA)$_{63}$] macro-CTA (E2) and without macro-CTA (E3).

Figure AII.5. Evolution of water uptake for films produced by surfactant free aqueous emulsion polymerisation at 40wt%, without (E3) and with P(SBMA)$_{248}$ macro-CTA (E1).

Annexe III
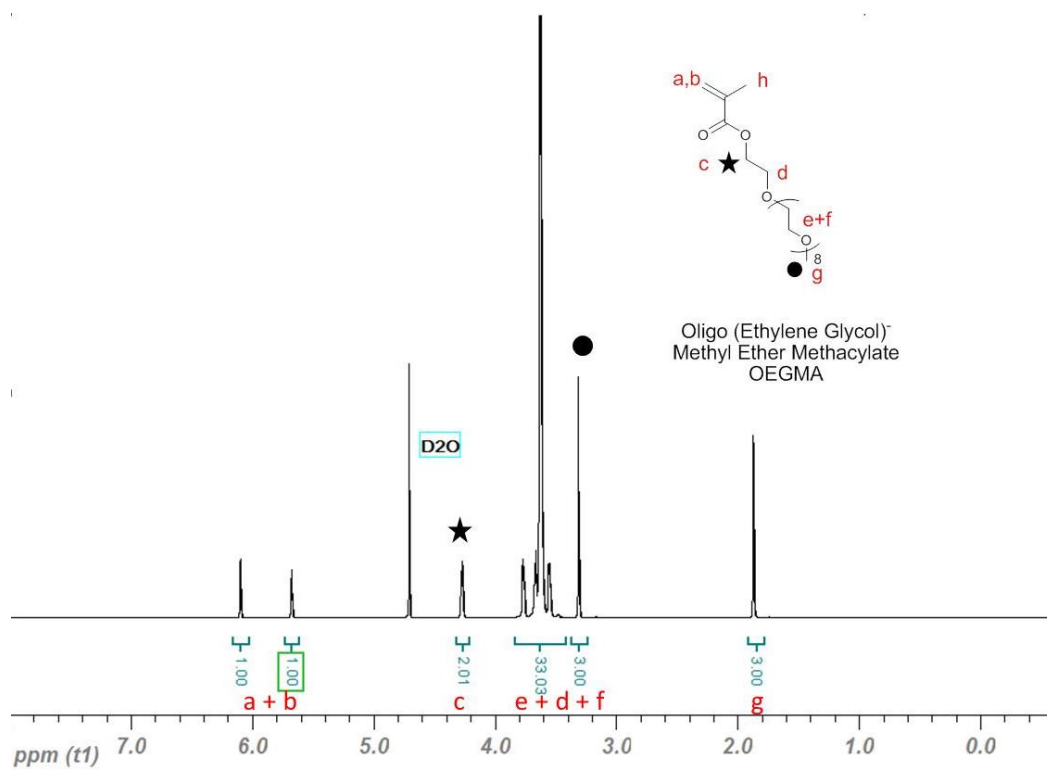
Figure AIII.1. ^{1}H NMR spectra recorded for OEGMA monomer in D_2O.
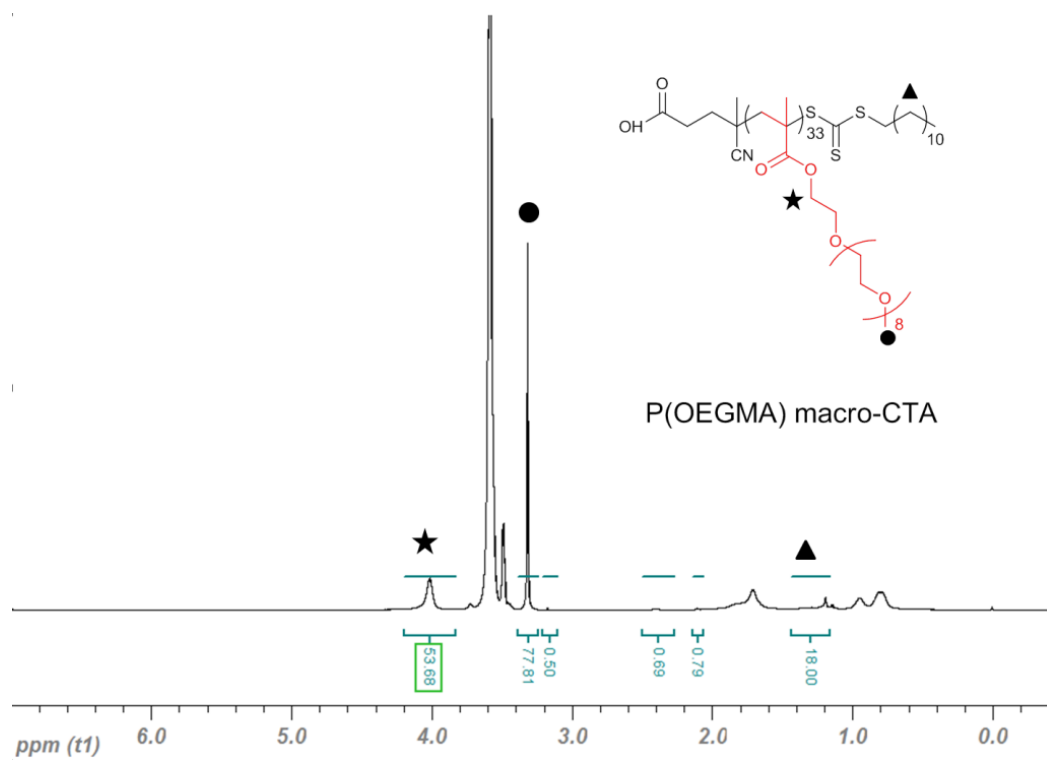
Figure AIII.2. ^{1}H NMR spectra recorded for POEGMA macro-CTA in CDCL$_3$.

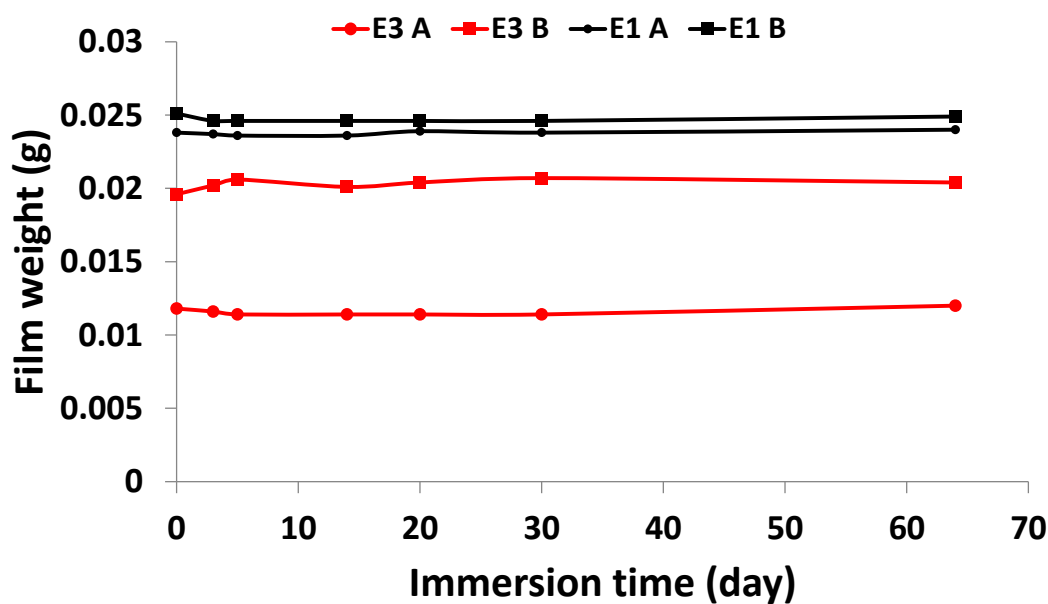**Figure AIII.3.** Gel permeation chromatogram curves (tetrahydrofuran eluent, refractive index detector) obtained for the free radical homopolymerisation of POEGMA. Calibration was achieved using a series of near monodisperse polystyrene standards.
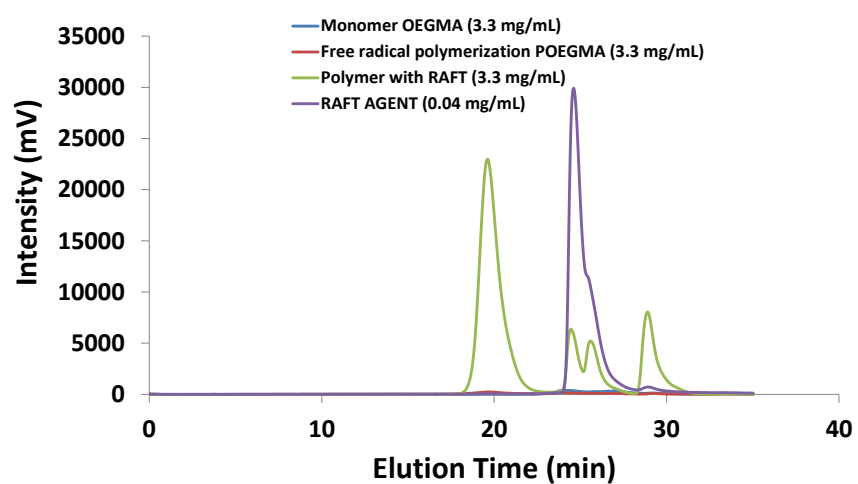
Figure AIII.4. Gel permeation chromatogram curves (tetrahydrofuran eluent, ultraviolet detector at 310 nm) obtained for the POEGMA synthesised with CDTPA RAFT agent (macro-CTA), CDTPA RAFT agent, OEGMA, POEGMA without CDTPA RAFT agent.
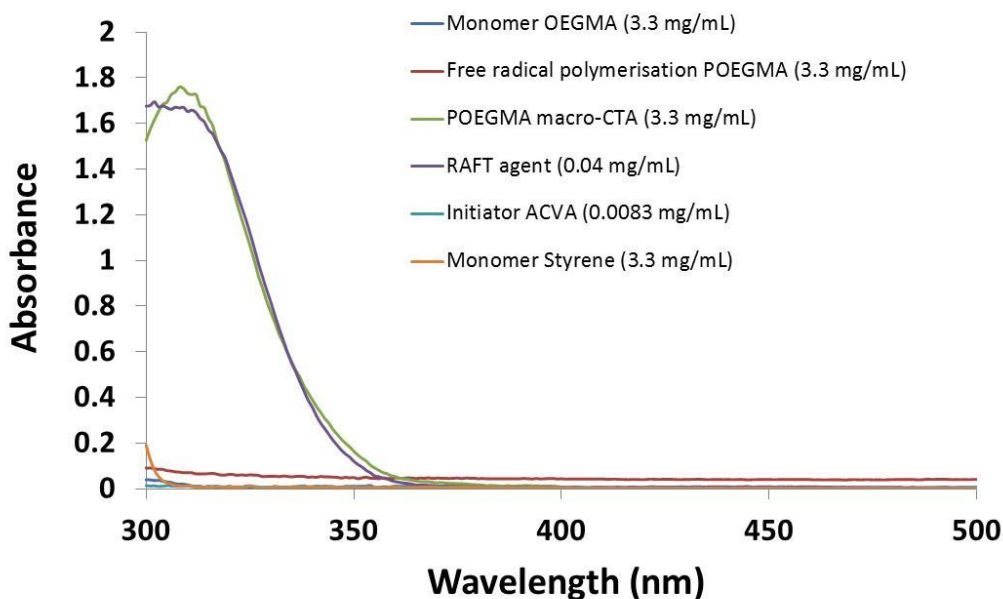
Figure AIII.5. UV-VIS absorption spectrum of OEGMA monomer (3.3 mg/mL), POEGMA homopolymer (3.3 mg/mL), POEGMA macro-CTA (3.3 mg/mL), 4-cyano-4-[(dodecylsulfanylthiocarbonyl)sulfanyl]pentanoic acid (97%) (CDTPA) RAFT agent (0.04 mg/mL), 4,4'-azobis(4-cyanovaleric acid) (ACVA) thermal initiator (0.0083 mg/mL) and styrene (3.3 mg/mL)
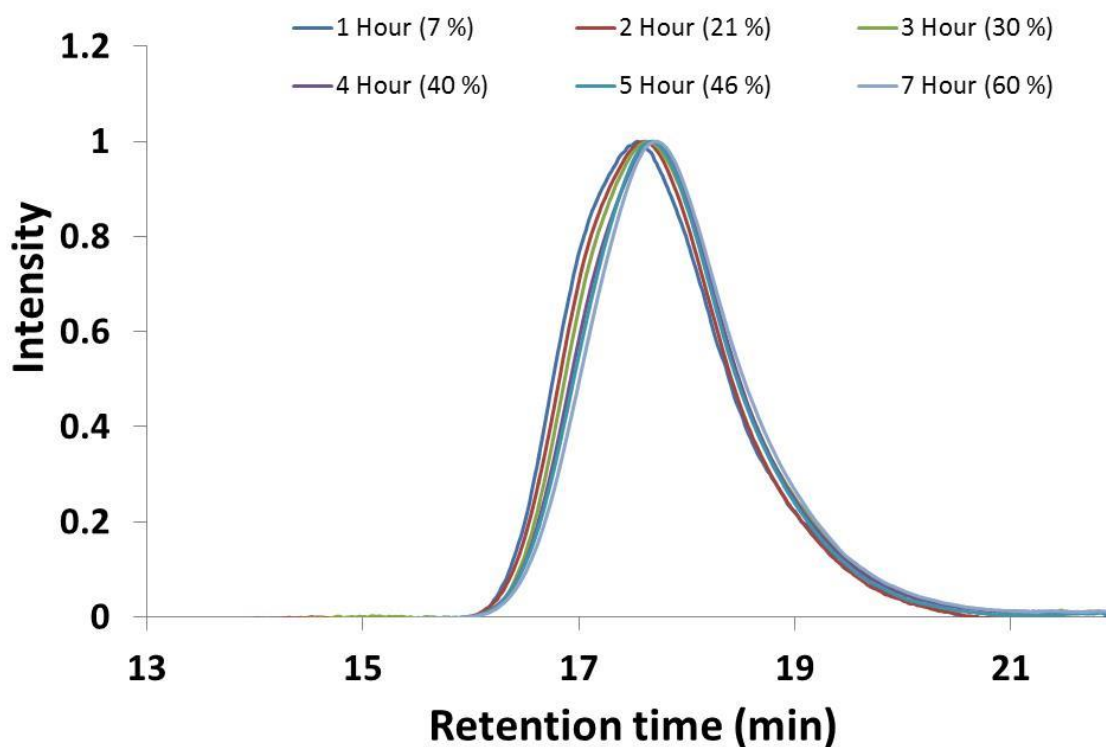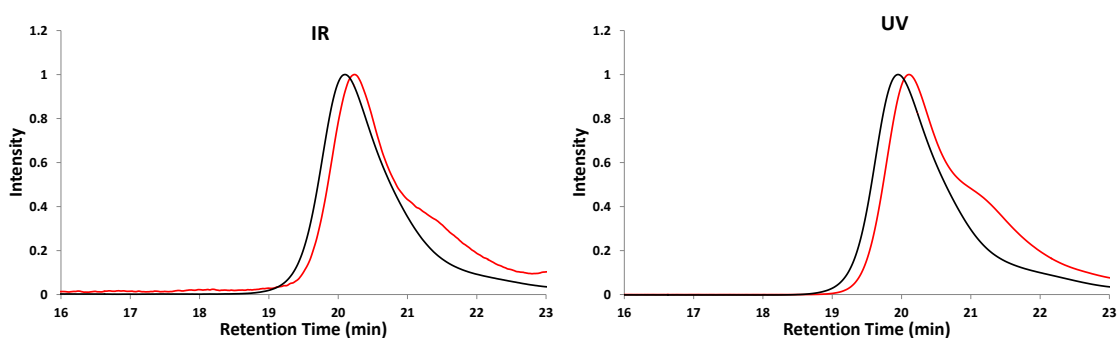

Figure AIII.6. Gel permeation chromatogram curves (tetrahydrofuran eluent, refractive index detector) obtained for the POEGMA RAFT polymerisation by 4-cyanopentanoic acid dithiobenzoate (CADB) RAFT agent. Calibration was achieved using a series of near monodisperse polystyrene standards. 8 Hours (-) and 18 Hours (-).
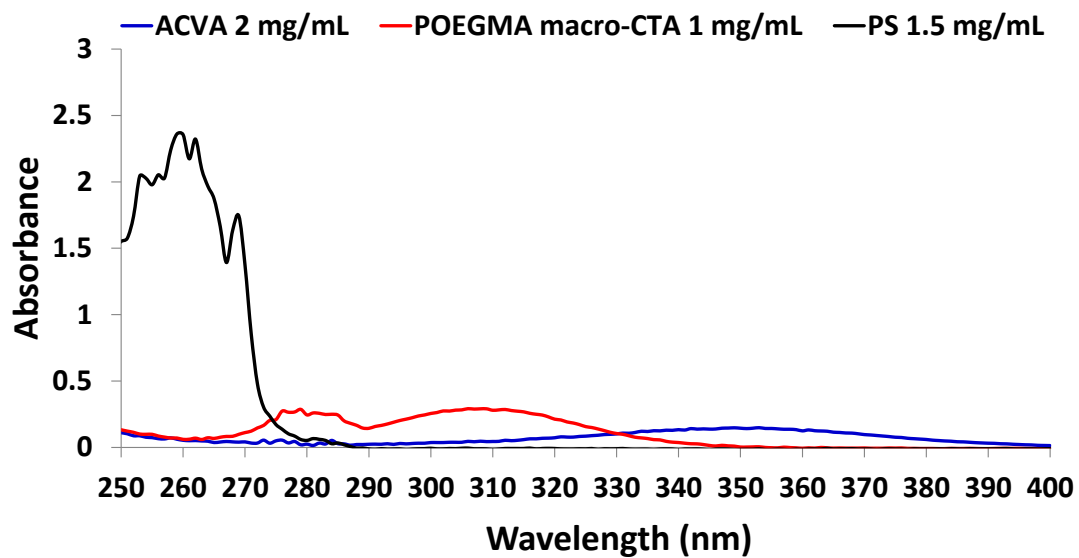
Figure AIII.7. UV-VIS absorption spectrum of ACVA (2 mg/mL), PS (1.5 mg/mL), and POEGMA (1 mg/mL).

Annexe IV

In relation to Chapter 4, graphene oxide (GO) sheets were incorporated during aqueous emulsion polymerisation mediated by POEGMA macro-CTA.

Experimental Section

Graphene oxide (GO) encapsulation via aqueous emulsion polymerisation mediated by POEGMA$_{27}$ macro-CTA

Firstly, the GO sheets were fragmented by sonicating Graphenea graphene oxide water dispersion (0.4 wt% concentration) for 13 h with ultrasonic (Hielscher ultrasound technology, UP400S) (Cycle = 1, Amplitude 100%), obtaining GO sheets with Dh < 300 nm (determined by DLS). After sonication, 1mg/mL GO sheets aqueous dispersion was prepared. Then, in a 25 mL flask, POEGMA$_{33}$ macro-CTA (10 mg, 0.0007 mmol), GO sheets (1 mg), initiator (3 mg, 0.011 mmol) and 9.9 mL deionised water were placed. The dispersion was stirred with magnetic stirrer and degassed with nitrogen for 30 min and subsequently styrene (100 mg, 1.1 mmol) and penthaerythritil tetacrylate crooslinker (1.7 µL, 0.0056 mmol) were added to the flask with syringe to produce 1 wt % of dispersion. The flask was placed in preheated oil bath at 70°C and 500 rpm. The reaction was left 22 hours and the polymerisation was quenched by immersing the flask in ice, followed by exposure to air. Monomer conversion and hydrodynamic diameter of the resulting particles were determined for each aliquot by gravimetric analysis, and dynamic light scattering (DLS), respectively. After the reaction, the dispersions were filtered and purified using semi-permeable cellulose tubing (SPECTRA/POR, corresponding to a molecular weight cut-off of 10,000 Da) changing the deionised water daily until the conductivity was constant.

Results and Discussion

Graphene oxide (GO) encapsulation via aqueous emulsion polymerisation mediated by POEGMA$_{27}$ macro-CTA

To optimise the reaction conditions, the stability of the GO sheets dispersed in water (0.01 wt %) as a function of pH and ionic stretch[1] was studied by light scattering and

zeta potential. As shown in Figure AIV.1 GO sheets begin to aggregate at pH 2 and at an ionic strength of 30 mM. Taking this results into account, the reactions were carried out at pH > 2 and using initiator concentrations < 30 mM.
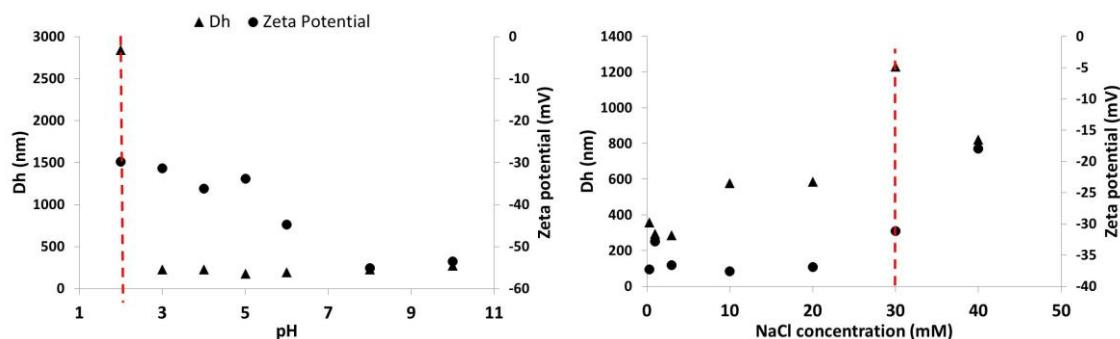

Figure AIV.1. Hydrodynamic diameter and Zeta Potential values of GO sheets at 0.01 wt % as a function of pH and NaCl concentration in water (in the case of pH, GO sheets aqueous dispersion was prepared in the presence of 0.1 mM NaCl).

Two different reactions, without (A1) and with $POEGMA_{27}$ macro-CTA (A2), were carried out in the presence of GO. While the dispersion synthesised with $POEGMA_{27}$ macro-CTA reached high conversion (65%), the dispersion produced without macro-CTA presented conversion below 20%. Likewise, in contrast to A2 formulation, in A1, at the end of the reaction, the GO sheets were precipitated at/on the bottom of the flask, demonstrating that GO sheets were not integrated in the PS particles.

Table AIV.1. Characterisation of polystyrene (PS) particles synthesised via aqueous emulsion polymerisation at 70°C using GO sheets.

code	GO	Dh_{GO} (nm)/PDI[a]	Zeta $_{Potential\ GO\ pH\ 4}$ (mV)[a]	$P(OEGMA)_{27}$[*]	Conv (%)[b]	$Dh_{composite}$ (nm)/PDI[a]	D[c]
A1	GO1	291	-38	-	20	243/0.24	180 ± 28
A2	GO1	291	-38	10 wt%	65	406/0.43	251 ± 46
B1	GO2	298	-16.5	-	75	267/0.27	-
B2	GO2	298	-16.5	10 wt %	86	128/0.19	75 ± 10

[a]dynamic light scattering (DLS) measurements at 25°C; reported values are an average of three measurements. [b]determined by gravimetric analysis. [c]measured by field-emission scanning electron microscopy (FE-SEM). At least 20 particles were counted in each case. *macro-CTA % based on monomer.

Furthermore, significant differences in terms of Dh and morphology of the particles were observed between both formulations, showing smaller particles in A1 (243 nm), compared to A2 (406 nm) formulation (see Figure AIV.1 and Table AIV.1). However, both

samples presented high polydispersity index in DLS measurements and it is well known that at in those cases DLS is not the most appropriate technique to determine the particles diameter. Regarding FE-SEM micrographs, particles diameters with 180 ± 28 nm and 251 ± 46 nm were found for A1 and A2 formulations, respectively. Moreover, Figure AIV.2 micrographs suggested that $POEGMA_{27}$ macro-CTA was affecting particles formation, creating raspberry like structure in A2 formulation.
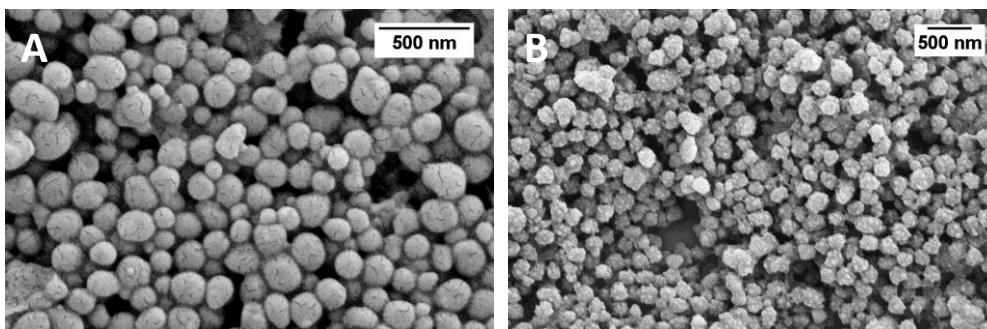
Figure AIV.2. FE-SEM micrographs of PS particles synthesised via aqueous emulsion polymerisation using GO sheets A) without $POEGMA_{27}$ and B) with $POEGMA_{27}$.

With the objective of studying the reproducibility of the technique, A1 and A2 reactions were repeated with another GO sheets batch (GO2). Unexpected results were obtained, both formulations (B1 75%, B2 86%) reaching high conversions and obtaining smaller particles (Table AIV.1). Moreover, the dispersions appearance suggests that, in both dispersions, GO sheets were integrated in the particles, not observing GO sheets precipitation (Figure AIV.3). Clearly, GO sheets batch was influencing on the efficiency and the kinetics of the reactions. However, once more, higher conversion was reached with the presence of the macro-CTA, corroborating that the influence of the stabiliser was important to reach high conversions.
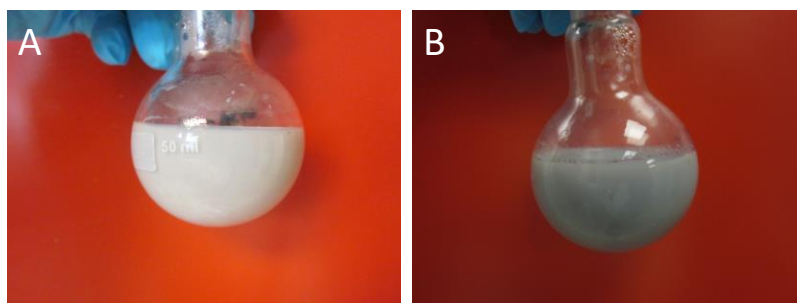
Figure AIV.3. Pictures of PS dispersion synthesised via aqueous emulsion polymerisation using GO sheets A) without $POEGMA_{27}$ and B) with $POEGMA_{27}$.

To examine with more details the morphology of the particles and the position of the GO sheets on the dispersion, the cryoTEM images in Figure AIV.1 were taken from the purified portion of the dispersions that were synthesised using POEGMA$_{27}$ macro-CTA. On A micrograph (Figure AIV.4), polystyrene particle were aggregated around the GO sheets creating particles with cauliflower structure. Nevertheless, A2 (Figure AIV.4, B) formulation displayed particles with armoured morphology in which the GO sheets were located at the particles surface. Because of the aggregates, particles with higher diameter were created in A2. The micrograph obtained by cryoTEM clearly demonstrated that GO sheets batch was influencing the particles morphology. This could be related to the fragmentation process of the GO sheets in which the GO sheets size and superficial charge was not accurately controlled by ultrasonication.
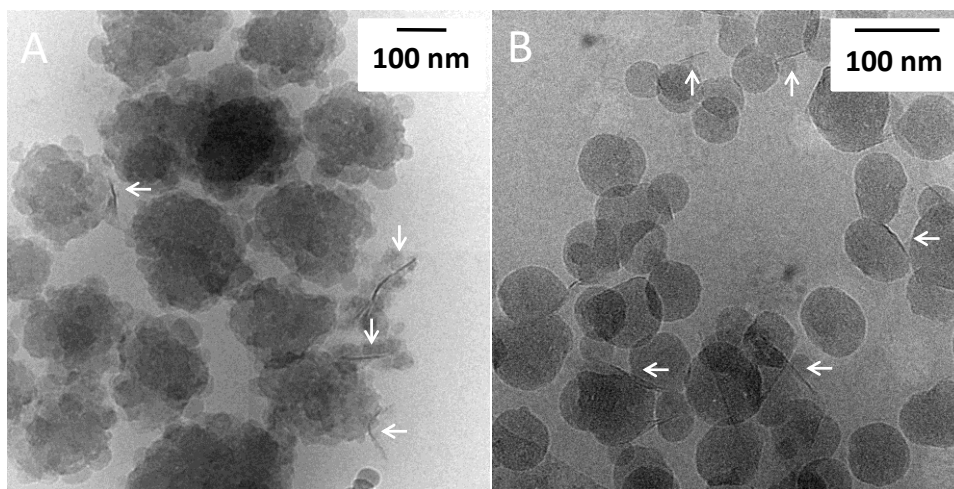
Figure AIV.4. Cryo-TEM micrographs of PS particles synthesised via aqueous emulsion polymerisation mediated by POEGMA$_{27}$ macro-CTA using two different GO sheets batches. A) A2 formulation (GO1). B) B2 formulation (GO2).

Due to the reproducibility problems of the fragmentation process of the GO sheets and consequently of the particles synthesis, further characterisation of the dispersions was not carried out.

Conclusions

GO sheets were incorporated in PS particles carrying out PS aqueous emulsion polymerisations. Once more, higher conversions were reached by the presence of the macro-CTA. However, GO sheets fragmentation process reproducibility problem were transfer to emulsion polymerisation reactions, obtaining different particles as a function of GO sheets batch.

Glossary

AA	Acrylic acid
ACVA	2,2'-(1,2-diazenediyl)bis(2-methylpropanimidamide) dihydrochloride
AFM	Atomic force microscopy
APS	Ammonium persulfate
ASW	Artificial sea water
ATRP	Atom-transfer radical polymerisation
BA	n-butyl acrylate
BSA	Bovine serum albumin
CA	Contact angle
CADB	4-Cyano-4-[(phenylcarbonothioyl)sulfanyl]pentanoic acid
CMC	Critical micelle concentration
CECSPA	4-Cyano-4-{[(ethylsulfanyl)carbonothioyl]sulfanyl}pentanoic acid
CLRP	Controlled/living radical polymerisation
CTA	Chain transfer agent
Dh	Hydrodynamic average particle diameter
DLS	Dynamic light scattering
DSC	Differential scanning calorimetry
DP	Degree of polymerisation
EtOH	Ethanol
FRP	Free radical polymerisation
FTIR	Fourier transformed infrared spectroscopy
GPC	Gel permeation chromatography (size exclusion chromatography/SEC)
^{1}H NMR	^{1}H Nuclear magnetic resonance

KPS	Potassium persulfate
Macro-CTA	Macromolecular chain transfer agents
MADIX	Macromolecular design via the Interchange of Xanthates)
Mn	Number-average molecular weight
Mw	Weight-average molecular weight
NMP	Nitroxide mediated polymerisation
Np	Number of particles
PDI	Polydispersity index
PEO	Polyethylene oxide
P(SBMA)	Poly[(2-methacryloyloxy)ethyl dimethyl-(3-sulfopropyl)ammonium hydroxide]
P(MPC)	Poly[2-(methacryloyloxy)ethyl 2-(trimethylammonio)ethyl phosphate]
P[(MAA)-co-(TMAEMA)]	Poly{[2(methacryloyloxy)ethyl]trimethylammonium-co-[methacrylic acid]}
P[(TMAEMA)-co-(SPMA)]	Poly{[(2-(methacryloyloxy)ethyl)trimethylammonium chloride]-co-[(3-sulfopropyl methacrylate potassium]}
POEGMA	Poly(oligoethyleneglycol methacrylate)
P[(PAHEMA)-co-(TMAEMA)]	Poly{[phosphoric acid 2-hydroxyethyl methacrylate]-co-[2(methacryloyloxy)ethyl]trimethylammonium}
PS	Polystyrene
PNA	Percentage net aperture
PNO	Percentage net occlusion
RAFT	Reversible addition-fragmentation chain transfer
RDRP	Reversible-deactivation radical polymerisation
TBT	Tributyltin
TEMPO	(2,2,6,6-Tetramethylpiperidin-1-yl)oxyl
TMSM	Trimethylsilyl methacrylate
ToF-SIMS	Time-of-flight secondary ion mass spectrometry

V-086	2,2´-Azobis[2-methyl-N-(2-hydroxyethyl)propionamide
V-50	2,2'-(1,2-Diazenediyl)bis(2-methylpropanimidamide) dihydrochloride dihydrochloride
VOC	Organic solvents from chemicals
X	Conversion
XPS	X-ray photoelectron spectroscopy

List of publication and conference presentation

*Below a list of **publications** will be published soon:*

Janire Alkorta, Laura Sánchez-Abella, Iraida Loinaz, Jose-Ramon Leiza and Damien Dupin. **"Development and characterisation of zwitterionic and pseudo-zwitterionic macro-CTA agents mediated polymer latexes"**. *Macromolecules.* In preparation.

Janire Alkorta, Laura Sánchez-Abella, Mischa Zelzer, Javier Rodriguez, Iraida Loinaz, Jose-Ramon Leiza and Damien Dupin. **"Synthesis and characterisation of ultrathin poly(zwitterionic) and poly(pseudo-zwitterionic) coatings via "grafting through" approach".** *Applied Surface Science.* In preparation.

Janire Alkorta, Laura Sánchez-Abella, Iraida Loinaz, Jose-Ramon Leiza and Damien Dupin. **"Synthesis of biocompatible nanoparticles via aqueous emulsion polymerisation stabilised through poly(oligoethyleneglycol methacrylate) trithiocarbonate chain transfer agent macromolecules (macro-CTA)"**. *Langmuir.* In preparation.

Oral presentation

Janire Alkorta, Laura Sánchez-Abella, Iraida Loinaz, Jose-Ramón Leiza, Hans-Jürgen Grande and Damien Dupin **"Poly(zwitterionic) and poly(pseudo-zwitterionic) macro-CTA-stabilised film-forming latexes as new waterborne antifouling coatings**". *Macromolecules.* European Student Colloid Conference, Varna, 2019.

Poster presentations

Janire Alkorta Salegi; Laura Sánchez Abella; Adrian Pérez San Vicente; Damien Dupin; Iraida Loinaz. **"Synthesis of self-stabilized biocompatible particles via RAFT aqueous emulsion polymerisation using PEGMA based trithiocarbonate macro-CTA"** eMRS-spring meeting, Lille, France.

Laburpena

Gainazal oro ur gazi zein gezatan urperatu eta minutu gutxira zenbait makromolekula biologiko (proteina, polisakarido eta proteoglikano) itsasten dira gainazalera, film bat eratuz. Ondoren, bizirik dauden organismoek, bakteriak, errotiferoak, protozooak eta diatomeak bezalakoak, gainazala kolonizatzen dute film biologikoa sortuz egun gutxiren buruan. Film biologiko honek, makro-alga, lanperna eta muskuiluak bezalako makroorganismoen finkapena eta itsaspena areagotzen du.

Desira gabeko atxikipen honek kalte larriak eragiten ditu ekonomian eta ingurumenean. Itsaspenak sortutako zimurdurak, itsas azpiegituren erresistentzia hidrodinamikoaren gorakada dakar berauen egonkortasuna gutxituz. Honen ondorioz, biokorrosioa gertatzeko probabilitatea handitzen da. Adibidez, itsasontzien kasuan, biofilmaren sorkuntzak erregaien erabileraren %40ko igoera eragiten du. Horrez gain, gertakari honek, itsasontzietan bidaiatzen duten espezie bitxien inbasioa areagotzen du bertako espezieak desagerraraziz eta hondamendi ekologiko handiak eraginez.

Kalte larri hauek ekiditeko modu askotariko estalkiak garatu dira azken urteotan itsaspenaren aurkako estrategia ezberdinak erabiliz. Oraintsu arte, zinka, kobrea eta eztainua bezalako konposatu erabili izan ohi dira gehien. Alabaina, 2008an, mundu mailan eztainuaren erabilera debekatu zuten bere bigarren mailako kalteak medio. Gaur egun, kobrearen erabilera ere mahai gainean dagoenez, ingurumena errespetatzen eta fouling-a ekiditen duten gainazal berriak aurkitzeko esfortzu handia egiten ari dira lurralde ezberdinetako zenbait ikerketa talde.

Estrategia desberdinen artean, besteak beste, jatorri naturaleko biozida ez toxikoak, tentsio baxuko gainazal elastomeroak, morfologia eta topografia desberdineko gainazalak, pultsu elektrikoa eta entzimen erabilera aurkitzen dira. Baina estrategia guztien artean, gainazal oso ur zaleak (hidrofiloak) azpimarratu behar dira. Material mota hauek modu eraginkor batean biofoulingaren erapena ekiditen dute, hidrogelen kasua den bezala. Kate polimerikoak elkarrekin loturik dauden hiru dimentsiotako egiturak dira hidrogelak, zeinak uretan disolbaezinak diren eta ur kantitate handiak absorbatzeko ahalmen (%99) duten. Mota honetako gainazalak asko erabili dira biomedikuntza alorrean modu eraginkor batean organismo biologikoen atxikipena

eragotziz. Konposatu oso hidrofiloen artean, polietilenglikola (PEG) da gehien erabiltzen den materiala, proteinen itsaspena saihesteko giltzarritzat, aldaratze esterikoak eta gainazalaren hidratazioa harturik. Alabaina, PEGak kontuan hartu beharreko oxidatzeko joera dauka, zeren eta oxidazioaren ondorioz biofoulingnaren aurkako propietateak galdu ditzake. Hori dela eta, monomero zwitterionikoak oinarri dituzten material polimerikoak hasi dira erabiltzen gainazal hidrofilo bezala.

Monomero zwitterionikoak, positiboki eta negatiboki kargatutako talde funtzionalak kate berean dituzten konposatu neutroak dira. Mota honetako polimeroen suaren, biofoulingaren eta proteinen aurkako propietateak ongi ezagunak dira gaur egun. Tamalez, nagusiki monomero hauen merkatuko balio altuengatik, berauen industrializazioa atzeratu da. Kosteak txikiagotzeko helburuarekin, ikerketa talde desberdinak, monomero kationiko eta anioniko portzentaia berdinak tartekatuz, kopolimero pseudo-zwitterioniak sintetizatu dituzte (polimero zwitteriokoen kopiak). Kopolimero pseudo-zwitterioniko hauek, karga neutroa izateaz gain, polimero zwitterionikoen proteinen aurkako propietate antzekoak aurkezten dituzte.

Zoritxarrez, modu honetako estalkiak (oso hidrofiloak, hidrogelak) ez dira gai mekanikoki itsaso zabaleko muturreko baldintza gogorrak jasateko. Horrez gain, estalki eraginkor hauek produzitzeko teknikak ez dira egokiak itsasontziak dituzte gainazal handiak estaltzeko.

Merkatuan dauden itsasontzien pintura komertzial gehienak konposatu organiko lurrunkor (VOC) kantitate handiak edukitzen dituzte. Lehen aipatu den moduan, gizartea gero eta kontzientziatuago dago ingurumenaren zainketarekin, beraz konposatu organiko hauen erabilera posible den heinean ekiditea nahi da. Uretan burutzen diren emultsio polimerizazioak hautabide egokia dira VOC kantitate txikiko pinturak produzitzeko. Gehienetan, pisu molekular baxuko tentsoaktiboak/egonkortzaileak erabiltzen dira uretan monomeroak polimerizatu eta emultsionatzeko. Hala eta guztiz ere, modu honetara produzitutako pinturak zenbait arazo aurkez ditzakete. Adibidez, tentsoaktiboren migrazioaren ondorioz filmaren opakutasuna eta ur xurgapena da. Film hauen propietateak hobetzeko helburuarekin, tentsoaktiboen ordez, partikulen gainazalera kobalenteki lotzen diren makromolekula

hidrofiloak erabili daitezkete egonkortzaile modura emultsio polimerizazioan. Prozesu hau aurrera eramateko modu bat, polimero hidrofiloak RAFT (*adizio-fragmentazio transferentzia itzulgarri)* bezalako polimerizazio teknika kontrolatu (CLRP) bat erabiliz sintetizatzea da. Ondoren, kate polimeriko hauek, monomero hidrofoboekin (ez ur zaleak) erreakzionatuz kate anfifilikoak eratuko dituzte, emultsio/dispertsio polimerizazioaren bitartez. Modu honetako kopolimerizazioak PISA (induzitutako auto muntatze polimerizazioa) bezala ezagutzen dira. Zehazki, RAFT teknikaren bidez lorturiko uretan disolbagarriak diren polimeroak erabiliz, azken hamarkadetan, mota desberdin askotariko dispertsioak eratu dira. Ideia hau ardatz hartuta, tesi honetan, itsasontzietako pinturak produzitu dira. Horretarako, lehendabizi RAFT teknikaren bitartez, polimero zwitterioniko eta pseudo-zwitterionikoak sintetizatu dira eta ondoren kateak luzatu, ur emultsio polimerizazioarekin.

Aipatu diren teknikak baliatuz, itsasontziak modu erraz batean estaltzeko propietate mekaniko onak dituzten pinturak sortuko dira. Horrez gain, egonkortzaile hidrofiloa partikulen gainazalean kokaturik egotean, desira diren foulingaren aurkako propietate emango dizkio estalkiari.

Lehenengo, koloideen eta polimerizazio teknika desberdinen inguruko laburpen bat egiten da. Horrez gain, gaur egun foulingari aurre egiteko erabiltzen diren polimerizazio teknika ezberdinak deskribatzen dira. Bukatzeko, tesiaren hipotesi eta helburu nagusiak plazaratzen dira labur-labur.

Ondoren, RAFT emultsio polimerizazio bidez produzitutako pinturetan, polimero zwitterionikoen eta pseudo-zwitterionikoen portaera nolakoa izango den aztertzeko helburuarekin, oso nanometro gutxiko gainazalak ekoitzi dira "grafting trought" teknika erabiliz. Kobalenteki geruza bakarreko gainazalak prestatzeko gehienbat hiru teknika erabiltzen dira. "Grafting to", "grafting from" eta "grafting trought". "Grafting trought", "grafting to" eta "grafting from" estrategien bitarteko teknika bezala ezagutzen da. Kate polimerikoak disoluzioan hazten dira haztarazlearekin. Propagazio etapan, gainazalera lotutako monomero batzuk hazkunde prozesuan kateekin integratu daitezke zuzenean polimero kateetara lotuz. Loturiko molekulak hazten jarraitu dezake gainazaletik disoluzioan daude monomero unitateekin erreakzionatuz.

Zoritxarrez ordea, hiru tekniketatik gutxien aztertutakoa da "grafting trought" zientziaren ikuspuntutik eta gaur egun oraindik ez daude oso garbi zein mekanismok hartzen duten parte polimerizazioan. Hori bai, produkzio ikuspuntutik, "grafting from" baina errazagoa da eta "grafting to" baino dentsitate handiagoko gainazal lortzen dira. "Grafting trought" teknika ardatz harturik zortzi hidrogel desberdin prestatu dira aurrez plasmarekin aktibatutako siliziozko eta beirazko xafletan, monomeroan jatorria (zwitterioniko-pseudo-zwitterioniko), solido edukia eta "cross-linkerra" aldatuz (cross-linkerrarekin edo gabe. Ondoren, gainazalen konposaketa kimikoa, propietate fisikoak, morfologia eta lodiera ikertu dira X-izpien espektroskopia (XPS), bigarren mailakako ioien hegaldi denboraren masa espektroskopia (TOF-SIMS), angelu kontaktu (CA), indar atomikoko mikroskopioa (AFM) eta ellipsometria teknikak erabiliz, hurrenez hurren. Teknika hauen bitartez, monomeroen banaketa gainazal osoan zehar berdina dela baieztatu da eta horrez gain < 5nm baino meheagoko lodierak dituzten filmak lortzeko/neurtzeko ahalmena daukagula erakutsi da. Azkenik "grafting trought" teknikaren bidez sintetizatutako gainazal zwitterioniko eta pseudo-zwitterionikoen proteinen itsaspenaren aurkako propietateak aztertu dira, bi (ko)polimeroen antzekotasuna egiaztatuz.

Behin film zwitterioniko eta pseudo-zwitterioniko oso finen foulingaren aurkako propietateak frogatu direnean, RAFT polimerizazio kontrolatuaren bitartez kate transferentzia agente makromolekular (macro-CTA) zwitterionikoak eta pseudozwitterionikoak sintetizatu dira, azkenengo kasuan monomero kationikoak eta anionikoak tartekatuz. Esklusio molekularreko kromatografia (SEC) eta erresonantzia magnetiko nuklearra (H NMR) erabili dira (ko)polimeroak karakterizatzeko. Modu kontrolatu batean RAFT polimerizazioaren bitartez "bizirik" eta karga neutroa duten (ko)polimeroak sintetizatu dira.

Ondoren macro-CTA hauek egonkortzaile eta kontrol agente bezala erabili dira butil akrilato/estireno/azido akriliko (60/38/2%) (ko)monomeroen ur emultsio (ko)polimerizazioan. Foulingaren aurkako propietate hoberenak dituzten estalkiak produzitzeko zenbait parametro ikertu dira, besteak beste, haztarazle mota, solido edukia eta kopolimero hidrofiloen luzera. Ondoren, 40 wt% solido edukia duten dispertsioak lortu dira 200 polimerizazio gradu teorikoa (DO) duten macro-CTA

zwitterinoikoak eta pseudo-zwitterionioak erabiliz. Filmak eratzen dituzten partikula hauek argiaren dispertsio dinamikoa (DLS), GPC, AFM eta ultravioleta (UV) espektroskopiaren bidez karakterizatu dira. Azkenik, polipropilenozko sareak pintatu dira, pinturen foulingaren aurkako propietateak aztertzeko egoera errealean (mediterraneko uretan urperatuta). Zoritxarrez, laborategian lortutako emaitzak onak izan arren (algen eta proteinen atxikimendua ekiditen dute), gure pinturak ez dira gai merkatuan dauden estalkien foulingaren aurkako propietateak hobetzeko itsaso zabalean.

PISA polimerizazioaren inguruan pixka bat gehiago sakontzeko helburuarekin, aplikazio erabat ezberdinak dituzten poliestirenozko partikulak sintetizatu dira polietilenglikol metil metakrilatozko (POEGMA) macro-CTA erabiliz, egonkortzaile eta kontrol agente bezala. Lehen aipatu den moduan, PEGa oso material famatua da biomedikuntza alorrean. Esate baterako, nanopartikulen propietateak hobetu ditzake egonkortasuna eta bateragarritasuna emanez. Baina, PEGren eragin kaltegarri batzuk medio (adibidez, gorputzeko immune sistemak PEGren aurkako antigorputzak sortu ditzake), PEGren ordez POEGMA erabiltzea erabaki da kasu honetan. Lehendabizi, RAFT polimerizazioaren bidez POEGMA macro-CTA polimerizatu da eta ondoren kateak luzatu estirenoarekin, ur emultsio polimerizazioan. Gainera, haztarazle kontzentrazioak emultsio polimerizazioaren zinetiketan eta macro-CTAren efizientzian daukan eragina aztertu da, H NMR eta GPC bitartez. Horrez gain, lorturiko partikulen morfologiak eta tamainak eskaneatze mikroskopio elektroniko (SEM) eta DLS laguntzarekin ikuskatu dira. Segidan, etorkizuneko aplikazioetan duten bideragarritasuna aztertzeko helburuarekin, partikulen zitotoxikotasuna neurtu da *Human dermal fibroblastoetan* (HDF). Espero zen moduan, haztarazle kantitateak eragin zuzena dauka partikulen berdintasunean. Zenbat eta haztarazle kontzentrazio handiagoa, orduan eta desberdintasun handiagoak partikula txiki eta handien tamainen artean. Horrez gain, haztarazle kontzentrazio altuek partikula ez esferikoen eraketa bultzatzen dutela ondorioztatu da. Alabaina, poliestirenozko partikuletara itsatsita dagoen POEGMA kantitatea ez dago zuzenki loturik haztarazle kontzentrazioarekin.

Azkenik, partikulen zitotoxikotasun eza baieztatuta da, partikulen morfologia eta tamaina edonolakoa izanda ere.