The University of Nottingham

UNITED KINGDOM • CHINA • MALAYSIA

Bio-Sourced Novel Monomers and Polymers for Plastics Sustainability

Norah Alshehri, MSci.

Thesis Submitted to the University of Nottingham for the degree of

Doctor of Philosophy

2025

ABSTRACT

This thesis details the synthesis of several novel monomers from biomass chemicals such as terpenes and furfural. Several synthesis routes were explored to produce a broad spectrum of functional groups suitable for polymerisation, such as hydroxyls, carboxy acids, epoxides, lactones, and methacrylate.

In chapter two, terpene-derived monomers were synthesised via the derivatisation of α-pinene, β-pinene, limonene and geraniol. This resulted in novel monomers with diols, hydroxy-carboxylic acids, di-carboxy acids and epoxides.

In chapter three, a six-membered ring lactone monomer was synthesised from furfural.

Some of these monomers have been used in synthesising sustainable polyesters and polymethacrylate, which contain a unique cyclohexane ring or a double bond in their backbone, making them suitable for post-polymerisation modification. The functionalisation of limonene, α-pinene, β-pinene and geraniol has enabled the synthesis of several renewably-sourced monomers to form terpene-derived polyesters. Step growth homo-polymerisation of diols, diacids and hydroxy-acid yields low molecular weights of novel polyesters. The limonene diol derivatives are demonstrated to function as co-monomers alongside a renewable diacid. The resultant polyesters display M_{ns} of up to 8400 g/mol. α-Pinene was used to synthesise dialcohols, which served as co-monomers with a renewable diacid, enabling the synthesis of two novel polyesters.

ACKNOWLEDGMENTS

I want to express my heartfelt gratitude to Professor Robert Stockman for allowing me to join his research group and for his unwavering support, encouragement, sincere advice, and continuous guidance. I will be eternally grateful. I would also like to thank all the members of the C13 lab, especially the Stockman group, as well as the analytical services team in the School of Chemistry and the technical staff.

A special thanks goes to my family, particularly my husband, to whom I am deeply indebted for his constant love, encouragement, and belief in my ability to overcome the most challenging and difficult times during my studies. I am also profoundly grateful to my children for their patience and understanding of the challenges I faced. Their presence and the strength I drew from looking into their eyes fuelled my determination and motivated me to overcome many obstacles.

Finally, I sincerely thank everyone who supported me, knowingly or unknowingly, throughout this journey.

ABBREVIATIONS

AchR – Achmatowicz reaction

AIBN – Azobisisobutyronitrile

APEs – Aliphatic Polyester

CCR – Corey–Chaykovsky reaction

CSA – Camphorsulfonic acid

CR – Cellulose Regenerates

DA – Diels Alder reaction

DBU – 1,8-Diazabicyclo[5.4.0]undec-7-ene

DCE – Dichloroethane

DCM – Dichloromethane

DDT – 1-Dodecanethiol

DMDO – Dimethyl dioxirane

DMSO – Dimethyl sulfoxide

EG – Ethylene glycol

FA – Furfuryl alcohol

KDa – kilo Dalton

LA – Lactic Acid

LO – Limonene Oxide

*m*CPBA – 3-Chloroperbenzoic acid

M_n – Number-average molecular weight

NBS – *N*-bromosuccinimide

NCS – *N*-chlorosuccinimide

NHC – N-heterocyclic Carbene

NMO – *N*-Methylmorpholine N-oxide

PA – Poly Amide

PCC – Pyridinium chlorochromate

PBAT – Polybutylene adipate terephthalate

PE – Polyethylne

PET – Polyethylene Terephthalate

PEF – Polyethylene Furanoate

PTT – Polytrimethylene Terephthalate

PP – Polypropylene

PHA – Polyhydroxyalkanoates

PBS – Polybutylene Succinate

PLA – Poly (Lactic Acid)

PLC – Poly Limonene Carbonate

PMs –Poly (menthide)s

PTSA – *p*-Toluenesulfonic acid

r. t. – Room temperature

rDA – retro-Diels-Alder reaction

Red-Al – sodium bis(2-methoxyethoxy)aluminum hydride solution

ROCOP – Ring-Opining Co-Polymerisation

ROP – Ring Opening Polymerisation

SCPC – Starch Containing Polymer Compounds

TBC – 1,5,7- triazabicyclo[4.4.0]dec-5-ene

Tds – Thermal decomposition temperature

TEACl – Tetraethylammonium chloride

TEMPO – 2,2,6,6-Tetramethyl-1-piperidinyloxy

T_g – Glass transition temperature

TLC – Thin Layer Chromatography

Tm – Melting temperature

TABLE OF CONTENTS

Chapter One:

1. Introduction

1.1 Plastics Sustainability

The term "plastic" originally referred to materials that were pliable and easily shaped. Over time, it has come to define a broader category of materials known as polymers. The word "polymer" means "many parts," referring to substances composed of long molecular chains made up of repeating units called monomers (Figure 1.1).[1] Natural polymers, such as polysaccharides, polynucleotides, and proteins, play a fundamental role in all aspects of life.[2] In contrast, synthetic polymers are artificially produced and have become indispensable in modern society. They are widely used in commodity and specialised applications, including construction, textiles, pharmaceuticals, medical devices, water purification, the silicon industry, oil, and energy.[3]

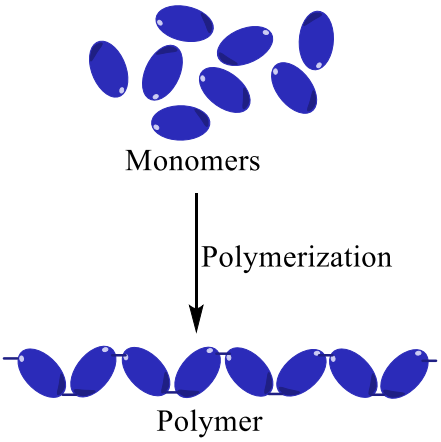


Figure 1.1: A schematic drawing of the principle of a polymer made of monomers.

There are two major mechanisms of polymerisation: step-growth (or condensation) polymerisation and chain-growth (or addition) polymerisation. Living polymerisation is a type

of chain growth polymerisation in which the capacity for a growing polymer chain to terminate has been eliminated.[4] The difference in the mechanisms is due to the difference in the active functional group in the starting monomers and the catalysts used to control these polymerisations.[4] Furthermore, polymers differ in their physical and chemical properties due to their differences in structures, functional groups, lengths of chains, interactions between the chains, etc.[4] Synthesis of new polymers requires either new compatible catalysts to initiate and control polymerisation or novel monomer structures with desired functional groups. In the last three decades, tremendous progress has been made in developing new polymerisation methods to afford new polymer structures.[4] These include living radical polymerisation,[5] olefin metathesis polymerisation,[6] stereospecific catalytic polymerisation,[7] late-transition-metal catalysis for olefin insertion polymerisation,[8] organo-catalysis for ring-opening polymerisation,[9] enzymatic polymerisation,[10] and supramolecular polymerisation.[11] These new methods have provided plenty of opportunities to design new generations of polymeric materials with increased complexity, functional and physical properties, structural precision and architecture.[5-11] Polymers can be classified as the source of the starting monomer, whether it comes from non-renewable or renewable resources. Crude oil is the major feedstock for polymers, which accounts for 7% of global oil consumption. According to European Plastics, this figure is estimated to rise to 20% by 2050.[12] More than 460 million metric tons of plastics were produced from non-renewable resources in 2022.[13] The rapid growth of the world's population has led to a rapid depletion of renewable resources, the overexploitation of the earth's resources, and an exponential increase of CO_2 emissions with significant consequences. These adverse effects, especially on climate change, have forced the economic powers to change from a linear model to a circular one. This approach focuses on preserving the added

value of the product for as long as possible, ensuring that resources stay within the production cycle even after the product has reached the end of its useful life (Figure 1.2).[14]

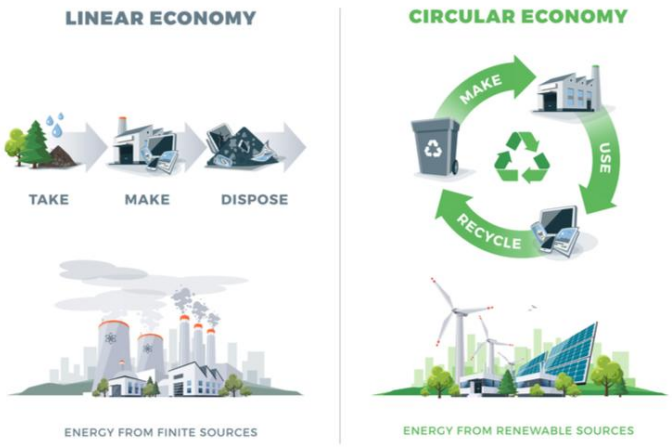


Figure 1.2: The difference between linear economy and circular economy.[13]

Circular economy considers the raw materials, energy use, production processes, by-products generated, industrial and consumer residues, packaging, transport, reuse, and recycling.[13] This offers excellent possibilities to create and sustain economic development and employment in rural regions, lessen reliance on fossil fuels, and enhance primary production and processing industries' economic, social, and environmental sustainability (Figure 1.2).[14,15] Thus, the growing interest in using renewable starting materials to make sustainable or bio-sourced plastics (bioplastics) are associated with various environmental advantages. European Bioplastics defines a plastic as a bioplastic if it is either derived from biological sources, capable of biodegrading, or possesses both characteristics.[13]

1.2 Bioplastics Resources

Bioplastics are plastics made from renewable biomass sources, such as plant fats and oils, maise starch, straw, woodchips, sawdust, and recovered food waste.[16] Some bioplastics are

made by processing polysaccharides (such as starch, cellulose, chitosan, and alginate) and proteins (such as soy protein, gluten, and gelatin) that are naturally occurring biopolymers.[16]

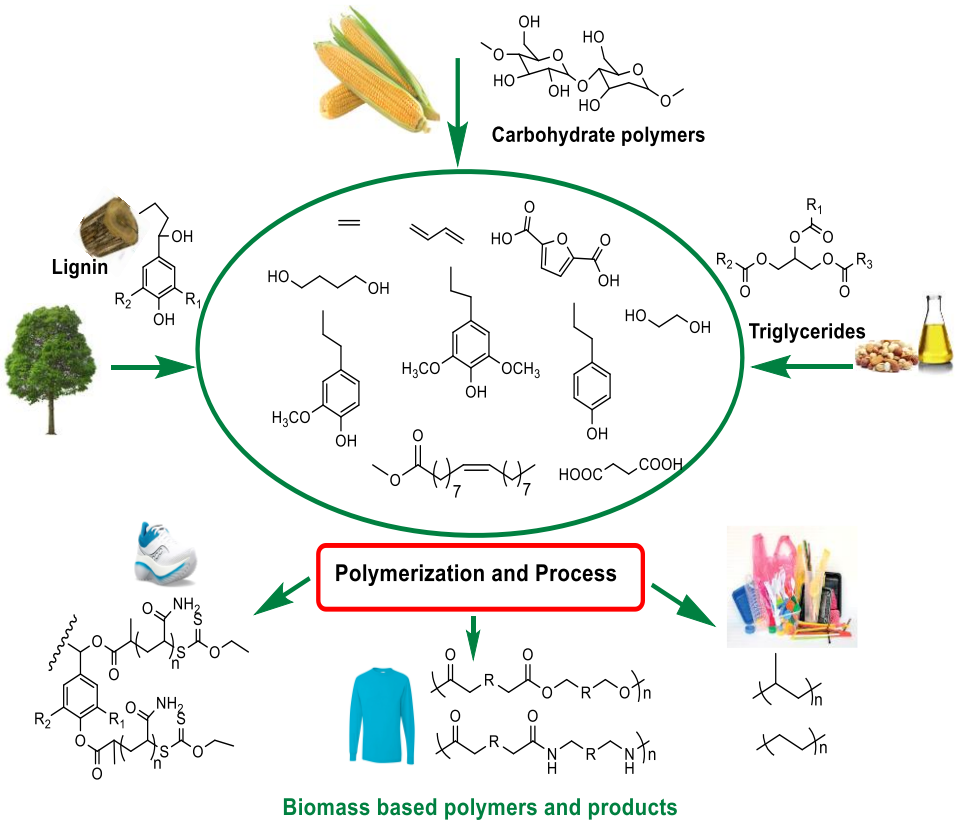


Figure 1.3: Common plastics used in our daily life come from bioresources material. [16]

Other bioplastics, on the other hand, are produced biologically through the fermentation of sugars or lipids or chemically from derivatives of sugar (such as lactic acid) and lipids (oils and fats) from either plants or animals (Figure 1.3).[16, 17] Bio-based plastics in Europe make up only 1% of the consumed plastics. However, global bioplastics production capacity is set to increase significantly from around 2.18 million tonnes in 2023 to approximately 7.43 million tonnes in 2028. The main applications for bioplastics are food services, packaging, agriculture, automotive, consumer electronics, consumer goods, and household appliances using different polymers (Figure 1.4). Packaging was the sector where the highest volume of bioplastics was used in 2020 (47%), followed by consumer goods (12%), textiles (11%), and covering coatings

(4%).[18] The advantages of bio-based materials can be summarised into non-fossil origin, lower carbon footprint emission of greenhouse gases and no toxins in their composition.[16-17] In contrast, some disadvantages exist, such as recycling issues, high-cost *vs* fossil, and inadequate legislation.[16-17]

Biodegradation refers to a chemical process where microorganisms present in the environment break down materials into natural substances like water, carbon dioxide, and compost, without the need for artificial additives.[16-17] The biodegradation process is influenced by various environmental factors, such as location and temperature, as well as the type of material and its application.[16-17] The ability to biodegrade is not determined by the source of a material but is instead related to its chemical composition.[16-17] This means that plastics that are fully biobased may not be biodegradable, while some plastics that are entirely fossil-based can indeed biodegrade. [16-17]

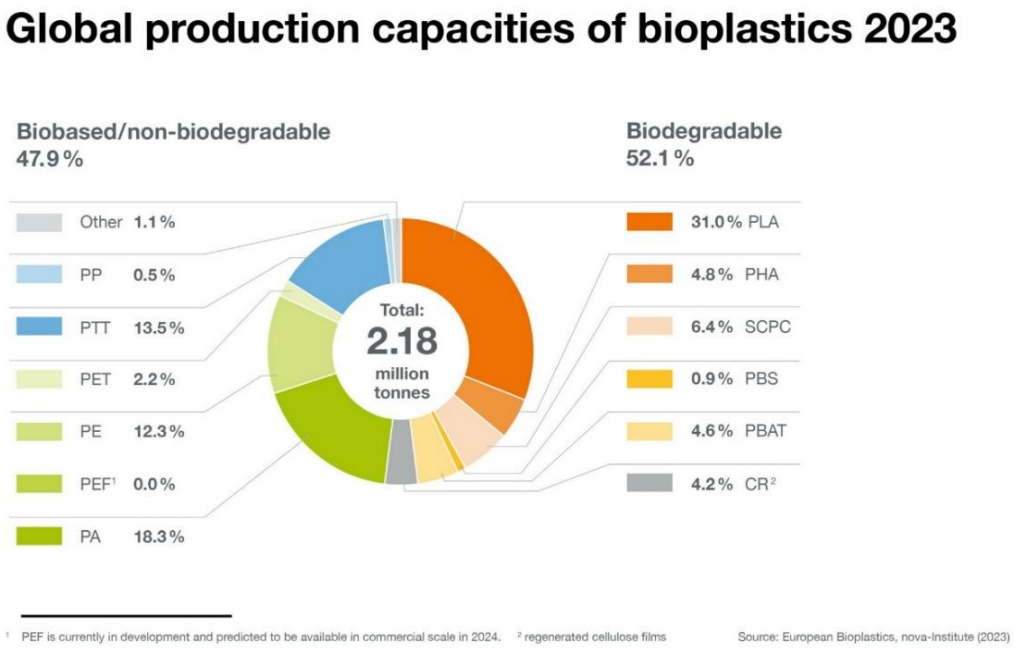


Figure 1.4: Global production capacities of bioplastics in 2023.[13]

A selection of the options available for use as feedstocks for renewable bioplastics is shown in Figure 1.5.

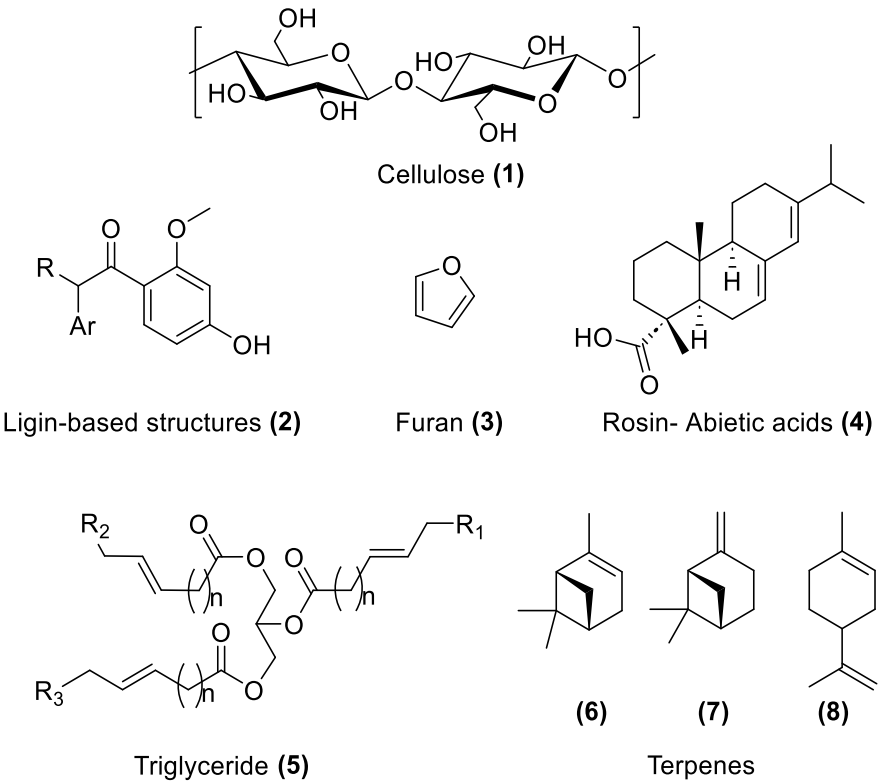


Figure 1.5: A selection of the options available for use as feedstocks for renewable bioplastics

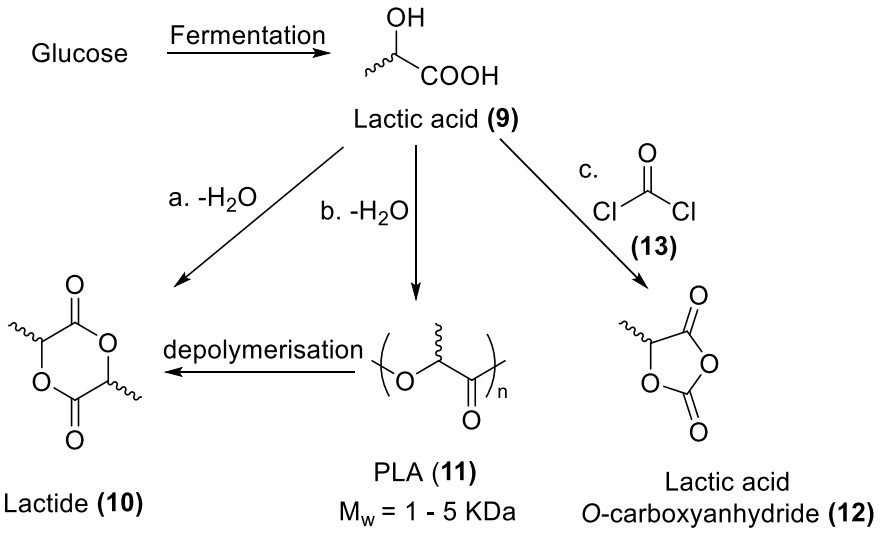
1.3 Sustainable Resources for Monomers and Polymers

1.3.1 Polysaccharides

Polysaccharides are natural polymers formed of repeating units of either monosaccharide (e.g., glucose, fructose, galactose) or disaccharides (e.g., sucrose, lactose) joined together by glycosidic bonds. Cellulose **(1)**, chitin, and starch are three of the most abundant natural polysaccharides. Generally, polysaccharides' most common chemical modifications are

through their primary OH groups.[19] Cellulose **(1)**, a polymer of D-glucose is present in plant cells in the form micro- and macrofibrils. It is used in paper, fabric, and natural fibres. From cellulose and its derivatives, four main fibre types are produced: viscose, lyocell, cupro, and acetate.[20] Starch can be obtained from vegetables like wheat, tapioca, potatoes, and maize, representing the highest share of the global production capacities of biodegradable plastics. Starch consists of amylose and amylopectin and is synthesised by most plants *via* photosynthesis.[21]

The monomer units of these polysaccharides have been used as feedstocks for chemical and fermentation processes to produce lactic acid **(**LA-**9)** or various dicarboxylic acids as monomers or monomer precursors. Lactide **(10)** is a six-membered cyclic diester and the dimer of lactic acid, the most widely occurring carboxylic acid in nature (Scheme 1.1).



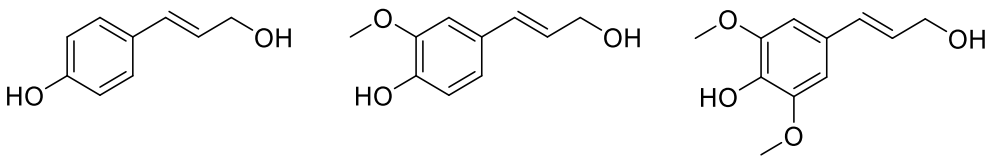
Scheme 1.1: Routes from LA to lactide via (a) zeolite-catalysed condensation and (b) oligomer depolymerisation (Mw: molecular weight). (c) Synthesis of lactic acid O-carboxyanhydride from LA.

LA is produced by the fermentation of biomass. Poly(lactic acid) (PLA - **11**) can be prepared by direct polycondensation of LA, but the process is better controlled by ring-opening polymerisation (ROP) of the cyclic precursor, lactide. Lactide is made by converting lactic acid into a low molecular weight prepolymer (molecular weight 1–5 kDa - **11**) using a homogeneous catalyst; tin 2-ethylhexanoate (tin octoate). Then, this is depolymerised to lactide through intramolecular esterification or backbiting (Scheme 1.1).[22]

Another monomer to produce PLA is lactic acid *O*-carboxyanhydride **(12)** which is made by reacting LA with phosgene **(13)**. When this monomer undergoes ring-opening polymerisation, one equivalent of carbon dioxide gas is released for every lactic acid unit incorporated into the polymer. PLA has received significant commercial attention as it displays suitable properties to replace polyolefins and potentially offers sustainability benefits over petrochemical-based polymers. PLA is an exceptionally successful renewable polymer due to its biomass origin and biocompatibility, and biodegradability, decomposing within the body into lactic acid, which the body converts to glucose through anaerobic respiration. This property makes it especially appealing for use in biomedical applications like drug or vaccine delivery and biodegradable screws, pins, and plates, which are designed to break down within six to twelve months.[23] A significant drawback of PLA is the need for high-quality land to grow corn to extract the starch. Currently, utilising waste CO_2 as an alternative carbon source is seen as a sustainable and innovative approach to reduce greenhouse gas emissions and create valuable products, such as fuels, chemicals, and materials. Technologies like carbon capture and utilisation (CCU) are gaining momentum.[24]

1.3.2 Lignin

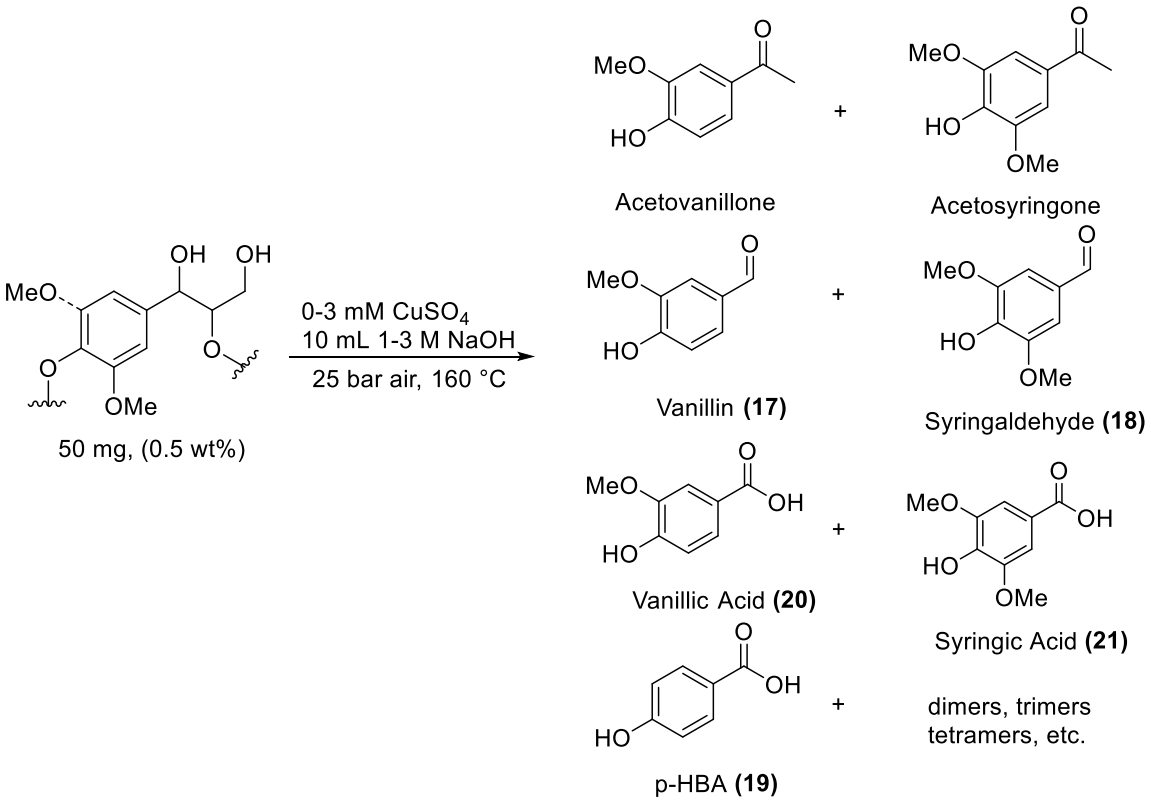
Lignin is a collection of phenol-based compounds obtained from wood, and it is the second most rich renewable resource of carbon, next to cellulose.[25] It may be defined as an irregular, oxygenated p-propylphenol supramolecular structure formed by the free radical polymerisation of monolignols.[25] The detailed structure of lignin varies from species to species and as a function of the age of a tree, although the presence of both phenolic and aliphatic hydroxyl groups, as well as of the typical "C9 motifs," consisting of an aromatic ring joined by three aliphatic carbon atoms, are familiar to all lignins (Figure 1.6).[25]



p-Coumaryl alcohol **(14)** Coniferyl alcohol **(15)** Sinapyl alcohol **(16)**

Figure 1.6: Typical "C9 motifs," consisting of an aromatic ring joined by three aliphatic carbon atoms as common lignins.

The amount of lignin extracted in pulping operations is estimated at over 70 Mt annually worldwide.[26] Only 2% is exploited as a source of chemicals or materials, as the majority is burned as energy for the process and the regeneration of the pulping catalysts.[26]



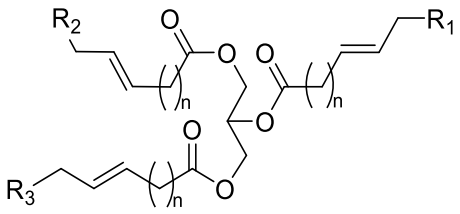
Scheme 1.2: Phenolic aldehydes and carboxylic acids produced by the oxidative fractionation of lignocellulosic biomass.[28]

The oxidative fractionation of lignocellulosic biomass, in the presence of Co-N-C catalysts and O_2 in acetone as a solvent, allowed high recovery efficiency of the components of lignin such as phenolic aldehydes and carboxylic acids (vanillin **(17)**, syringaldehyde **(18)**, *p*-hydroxybenzoic acid **(19)**, vanillic acid **(20)**, and syringic acid **(21)**) (Scheme 1.2)[27,28] which all are either useable as polymers starting monomers or modifiable by organic chemical reactions to make them polymer precursors. The standard methods to convert lignin into compounds of interest generally follow the sequence (i) fractionation of lignocellulosic biomass (pulping), (ii) lignin depolymerisation, and (iii) synthesis of specific chemicals. Different fractionation is carried out from other reaction mechanisms but mainly through the cleavage of ether bonds present in native lignin, which releases lignin fragments that remain in solution (black liquor).[28, 29] In all cases, a careful choice of the biomass fractionation process,

ideally avoiding extensive side reactions of lignin, produces promising aromatic building blocks for polymer synthesis. In general, the exploitation of lignin fragments to prepare macromolecular materials consists of three main approaches, namely (i) their use as blend components, (ii) their direct use as macromonomers in polycondensation reactions or to prepare carbon fibres, and (iii) their chemical modification before they intervened in the synthesis of a polymer.[26]

1.3.3 Vegetable or plant oils

Vegetable or plant oils are a huge family of natural viscous liquids sharing a common triglyceride molecular structure (Figure 1.7), in which R1, R2, and R3 correspond to fatty acid chains. Triglyceride **(5)** is extracted from vegetable oils and converted to glycerol plus fatty acids, methyl esters, and fatty alcohols. Subsequently, chemical modification steps are often conducted to obtain the specific chemicals of interest. Here, we will discuss glycerol and fatty acids as the most useable compounds for polymer synthesis.



Triglyceride **(5)**

Figure 1.7: Chemical structure of triglyceride, while n is the number of the CH_2 in the side chain of the fatty acids.

1.3.3.1 Fatty acids

The fatty chains of triglycerides vary widely depending on the source from which they were extracted. Almost 90% of all vegetable oil that is produced and distributed around the world comes from soybean (Glycine max), sunflower (Helianthus annuus) seeds, palm (Elaeis

guineensis), rapeseed (Brassica napus), with oleic **(22)** and linoleic acids **(23)** as their primary fatty acids, followed by palmitic **(24)**, stearic **(25)**, and linolenic acids **(26)** (Figure 1.8).[29] Up to 20 different fatty acids, with n= 14–22 carbon atoms, have already been identified in appreciable quantities in vegetable oils.[26]

As vegetable oils are widely used for food and feed, as well as for energy generation and to produce chemicals and materials, they are often classified as the most critical renewable feedstocks of the chemical industry.[26] The main characteristics that determine the physicochemical properties of fatty acids are the length of the heavy acid chains (n of CH_2 units), the stereochemistry of the double bonds (*Z* or *E*), and the degree of olefination. For decades, fatty acids were preferred for polymer synthesis among other bioresources due to their abundance and geographical distribution, low price, ease of chemical modification, and potential biodegradability of the final materials.

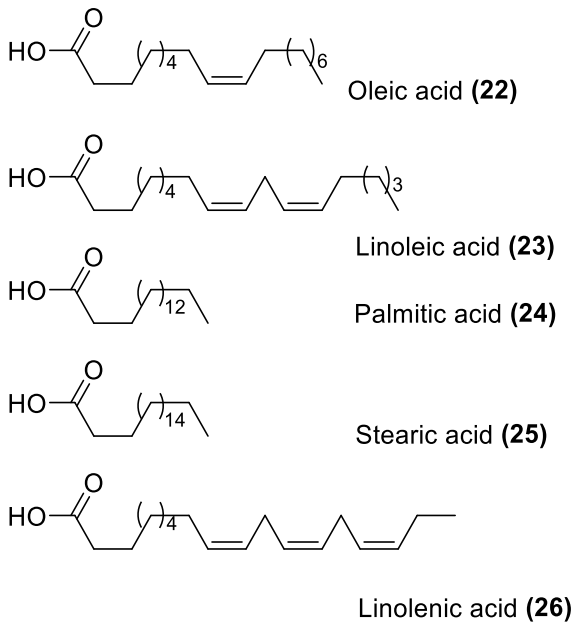
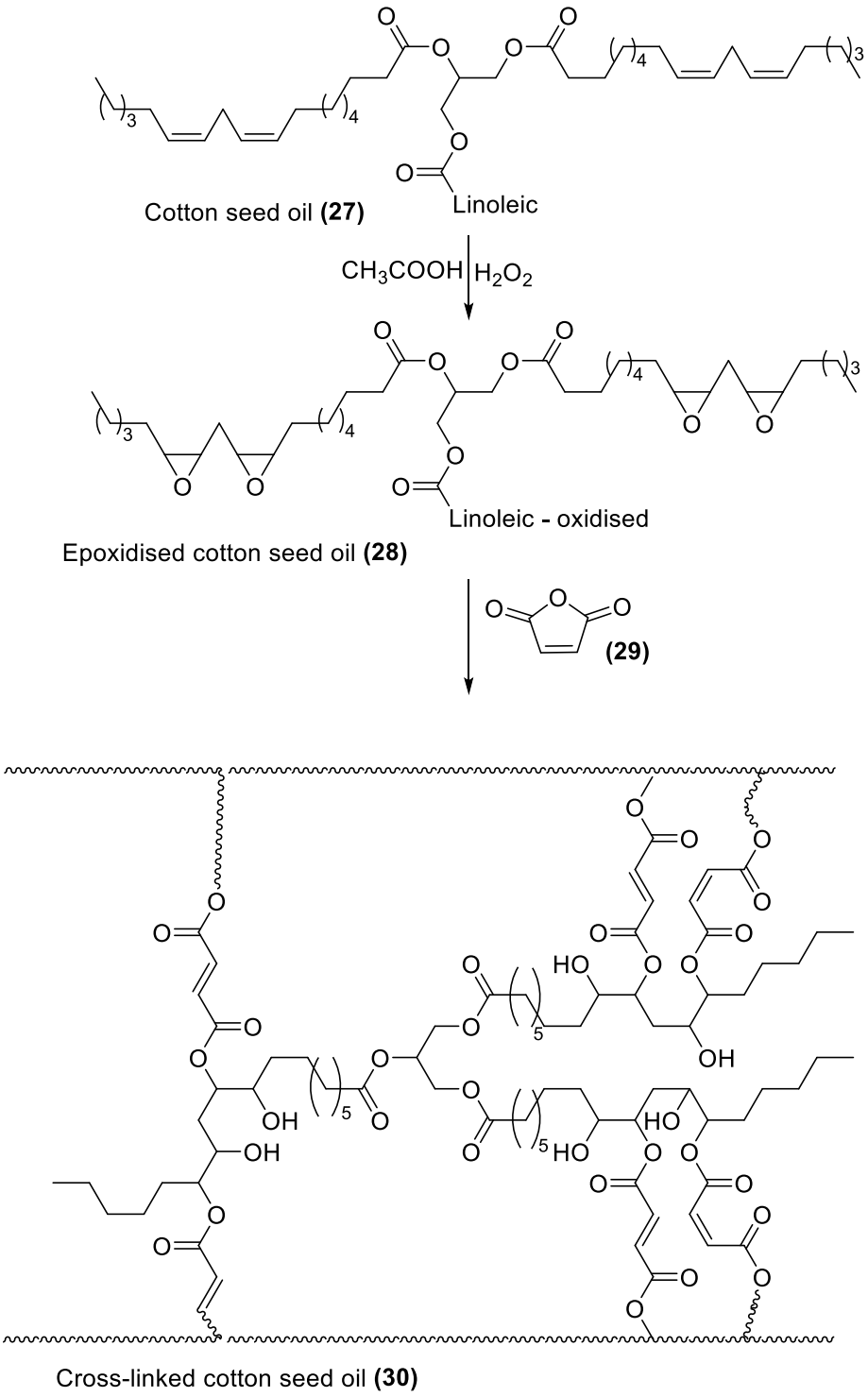


Figure 1.8: Molecular representation of a generic structure of most common available fatty acids.

A book focused on the production of vegetable oil-based polymers was published a few years ago.[30] In the last 20 years, the development of novel UV-curable coatings, polyamides, polycarbonates, polyurethanes, polyesters, and other materials based on vegetable oils, has been described.[30, 32] This free radical crosslinking oxy-polymerisation involves the initial abstraction of a hydrogen atom from the methylene group positioned next to a double bond, which leads to the formation of peroxy radicals. In a later step, the recombination of radicals produces crosslinks (alkyl, ether, or peroxide). Therefore, the degree of unsaturation is a factor of considerable importance since the double bonds present along the chains are the promoters of many possible functionalisation reactions for the chemical industry.[26]

Wijayapala *et al.* prepared crosslinked polymers from cottonseed oil by epoxidising the double bonds of the linoleic chains of the triglyceride and then reacting the epoxide version with maleic anhydride **(29)** (Scheme 1.3).[33] These polymers' mechanical characteristics were changed by changing the amount of maleic anhydride. These polymers are stable in both an acidic and an alkaline environment and have a tensile modulus of the order of 1 MPa.[26,33]

This is a versatile approach, as epoxy thermosets based on vegetable oils may be produced with extensive properties depending on the specific raw material, reaction characteristics, and comonomers employed. Furthermore, these are fully renewable thermoset polymers, and their potential biodegradability was assessed in alkaline and compost conditions. Recent contributions in the field of polymer science highlight a growing trend beyond merely focusing on the synthesis of plant oil-based thermosets. Researchers are increasingly prioritising a comprehensive evaluation of the final materials' properties, particularly their performance at the end of life and their environmental impact. This shift aligns with the principles of circular economy and sustainable materials development.[33]



Scheme 1.3: Reaction scheme for the cross-polymerisation of cottonseed oil with maleic anhydride.[33]

1.3.3.2 Glycerol

It is not only the fatty acid constituent of vegetable oils that can be utilised as bio-starting materials for polymers. Glycerol **(31)** is the second high-value by-product of vegetable oils, which can be used as a precursor for producing novel high-value-added products. Glycerol is a versatile compound susceptible to many (bio)chemical conversions, leading to very interesting building blocks for preparing a large family of chemicals (Figure 1.9). Glycerol ethers, for instance, meet the requirements of renewable green solvents and have attracted much attention in various applications.[34] The chemical structure of glycerol makes it a fascinating platform chemical for conversion into other chemicals, and it can also be used directly in polycondensation reactions to make polyesters. Microbial bio-transformations of glycerol, mainly into dihydroxyacetone **(33)**, are catching the attention of the researchers.[35] Many of glycerol's derivatives are also suitable for polymer synthesis.[36] For instance, glyceric acid **(32)**, dihydroxyacetone **(33)**, mesooxalic acid **(34)**, hydroxypyruvic acid **(35)**, tartronic acid **(36)** and others (Figure 1.9) have great potential as starting materials for monomers or polymer synthesis.[26] The most common reactions of glycerol to produce these derivatives are selective oxidation, hydrogenolysis, dehydration, and esterification with particular protections (Figure 1.9).

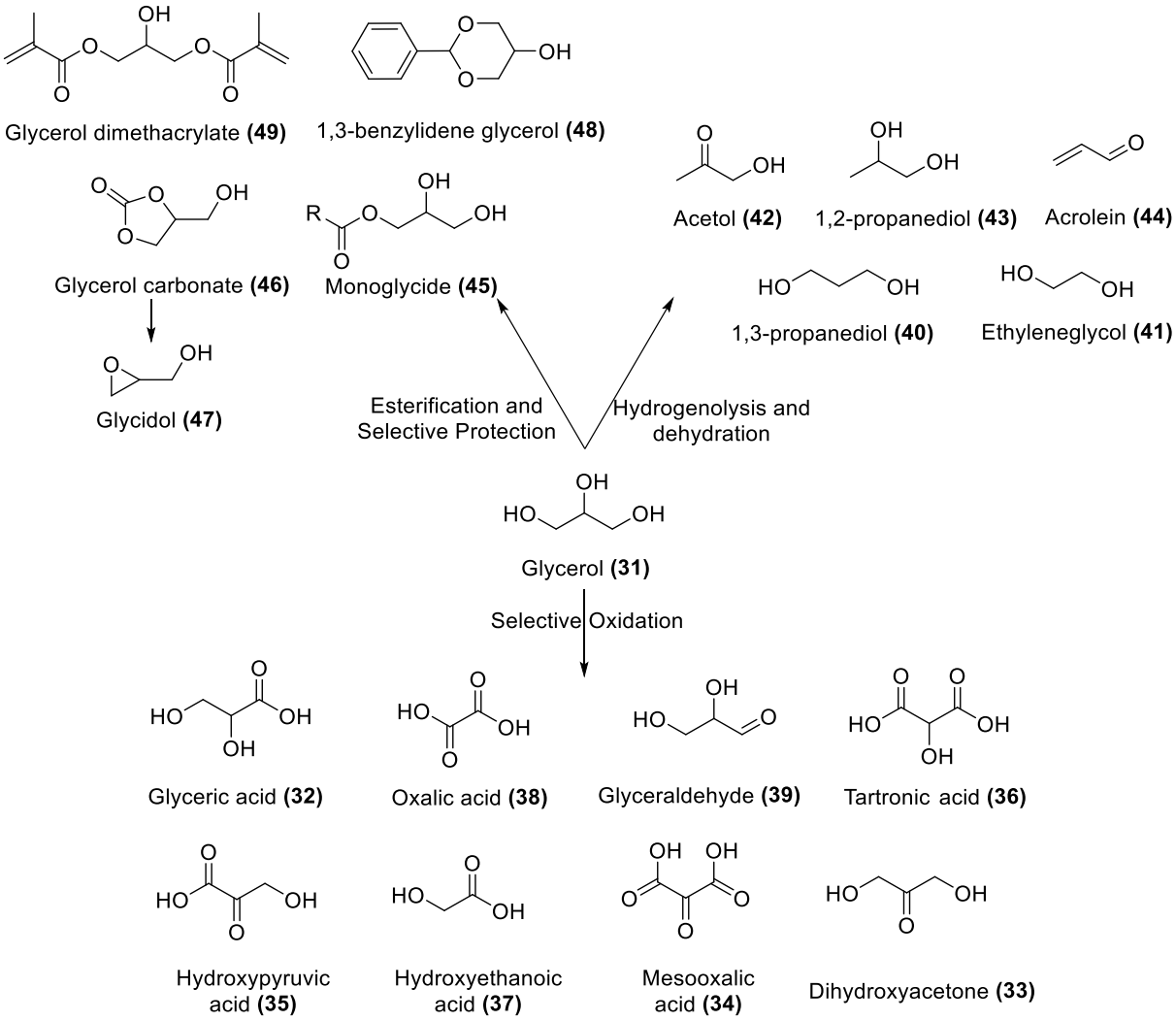


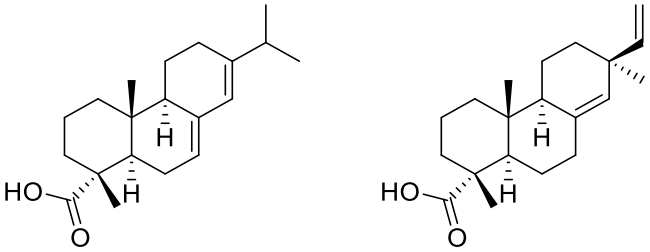
Figure 1.9: Conversion of glycerol into value-added compounds via different catalytic pathways

Glycerol-based polymeric materials find applications in the food, pharmaceutical, cosmetic, and polymer industries.[26] Polyglycerols are produced either from epichlorohydrin or directly in the presence of a strong base. However, epichlorohydrin is classified as a probable carcinogenic material. Hence, searching for non-toxic counterparts is essential for the cosmetic and food sectors. A review article published by Ebadipour and coworkers indicates that alkaline homogeneous and heterogeneous catalysis might be strategic routes to yield glycerol-based polymers, as they offer higher glycerol conversions.[37] Glycerol carbonate can be synthesised from crude glycerol and urea, which can then be converted to polycarbonates, polyglycerol

esters, hyperbranched polyols, and non-isocyanate polyurethanes using zinc, magnesium, tungsten, and ionic liquid-based catalysts.[38] Poly(glycerol sebacate) with varying molar ratios of glycerol, sorbitol, sebacic acid, 1,6-hexanediol or 1,8-octanediol, were synthesised using the enzyme Candida antarctica lipase B, yielding semi-crystalline materials that could be processed by electrospinning and exhibited potential to be applied in the biomedical field.[39,40]

1.3.4 Rosin

Rosin, also called colophony or Greek pitch, is a solid resinous substance derived from pine trees and certain other plants, primarily conifers, created by heating the fresh liquid resin to vaporise the volatile liquid terpene elements.[41] Rosin acids also offer another option for potential bioplastic production (Figure 1.10). Like fatty acids, these materials contain a carboxylic acid group in conjunction with several alkenes.[41]



Abietic acids **(4)** Pimaric acid **(50)**

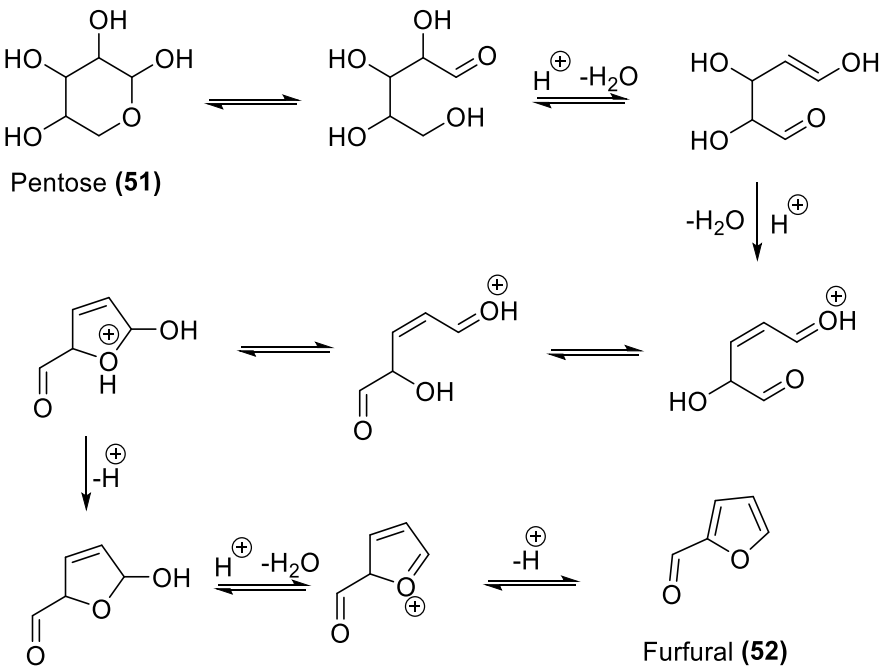
Figure 1.10: The structure of some examples of rosin acids, abietic acid (4) and pimaric acid (50), available in nature.

Direct esterification of these alkenes, or their conversion into alcohols via a Brown hydroboration/oxidation before esterification, could potentially allow the production of polyesters from these starting materials. Unfortunately, the problem with the use of rosin acids on a large scale is that they are not produced in large quantities in nature when compared with other bioplastic options. Most rosin acids come from crude tall oil and the scale of rosin acid production in 1994 was 265,000 metric tons, with the majority of this going towards the

production of diesel additives.[41] Therefore, achieving the amounts required for mass polymer production would be a significant challenge. Also, the structures within the family of rosin acids are reasonably limited, and providing a multitude of materials with different properties would also be difficult - however, some examples are documented in the literature. Rosin acids are synthesised in nature from isoprene, a ubiquitous starting material that is also the source of many other compounds, forming the terpenes family. This wider family gives a lot more options for the production of bioplastics from isoprene-based materials.[42,43]

1.3.5 Furans

Exploiting furans within the context of polymer chemistry has become one of the most relevant aspects of renewable resources.[44]



Scheme 1.4: Mechanistic scenario for the dehydration of pentose to furfural

The strategy relies on the exploitation of a derivative readily available from simple chemical transformations of natural polysaccharides: pentose (**51**)-containing polysaccharides constitute

the primary source of furfural **(52)** (Scheme 1.4).[44] Furfural **52** is the precursor of many monomers that have been successfully synthesised, characterised, and polymerised (Figure 1.11).[45–50] The industrial furfural production is estimated at 300 kt/year, costing approximately USD 1/kg. Two main strategies are possible to produce polymers from furan-based building blocks; the synthesis of furan-based monomers that are suitable for chain (co)polymerisations, forming macromolecules with pendant furan moieties.[26] This strategy is mainly based on furfural, an important platform for synthesising unsaturated furans (Figure 1.11), whose susceptibility to polymerise via chain reactions depends on their specific structure and their actual response to different types of initiation.

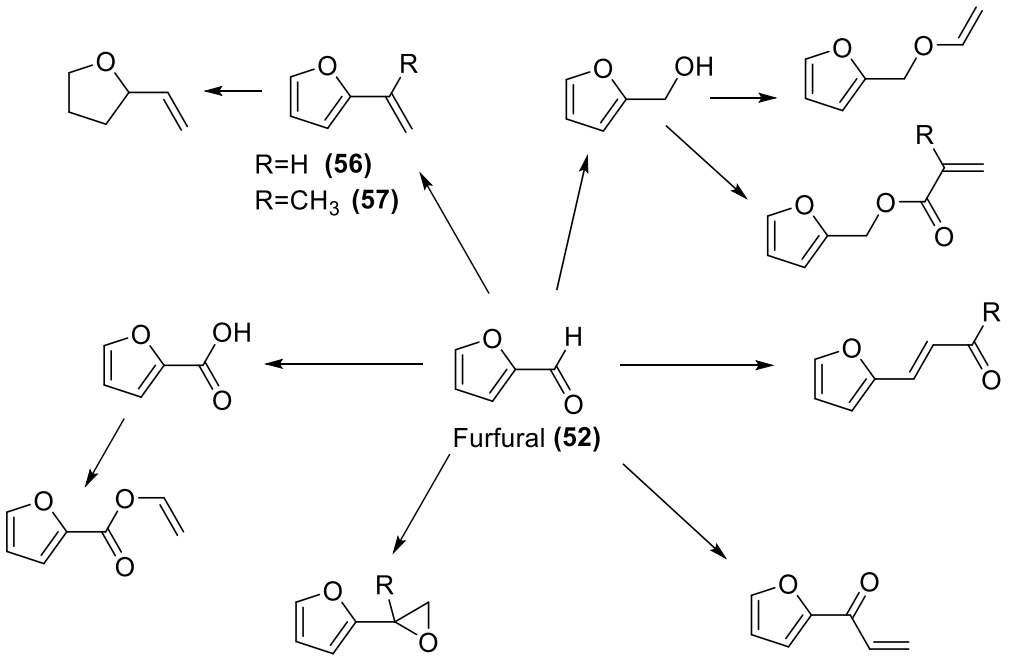
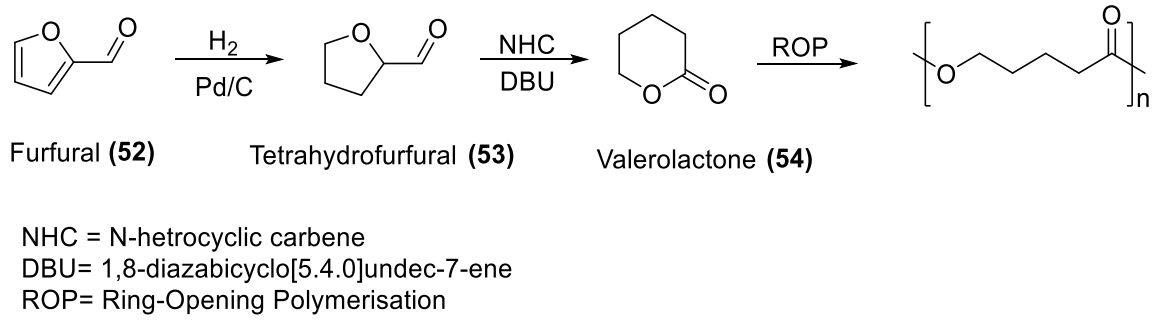


Figure 1.11: Furfural as a precursor to some furan monomers that can be polymerised by chain-growth mechanism

The other strategy is converting furfural into non-furan-based monomers such as hydroxy acids or their cyclic counterparts. For example, furfural can be reduced selectively to tetrahydrofurfural, followed by ring-expansion to δ-valerolactone **54** by means of an N-

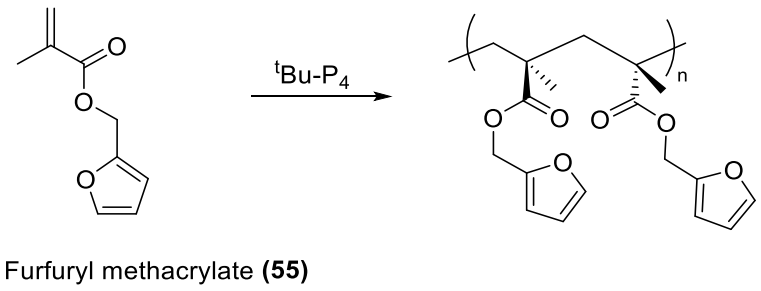
heterocyclic carbene.[51] δ-Valerolactone **54** can be polymerised via ring-opening polymerisation to afford a polyester (Scheme 1.5).



Scheme 1.5: Converting furfual into anther polymer precursor (valerolactone) to obtain a polyester poly(valerolactone).

The three main routes to furan-based chain polymers (i.e., *via* free radical, cationic, and anionic polymerisation) exhibit specific behaviours due to the dienic character of the furan ring that influences the stability of intermediates formed after a homo- or heterolytic cleavage of conjugated double bonds. Although only a modest number of furan monomers respond adequately to free radical initiation (as in the case of furfuryl acrylate and methacrylate **55**) (Scheme 1.6), ionic polymerisation may also be considered and sometimes yields interesting macromolecular materials. Feng *et al.* reported the polymerisation of furfuryl methacrylate **55** at ambient temperature (Scheme 1.6) by the P_4-phosphazene superbase, 1- tert -butyl-4,4,4-tris(dimethylamino)-2,2- bis[tris(dimethylamino)-phosphoranylidenamino]- 2λ5 ,4λ5 -catenadi(phosphazene) (^{t}Bu-P_4), producing syndiorich atactic poly(furfuryl methacrylate).[52] Tacticity is the relative stereochemistry of adjacent chiral centres within a macromolecule. The importance of tacticity in a macromolecule lies in its impact on the physical characteristics of the polymer. The consistency of the macromolecular arrangement affects whether it exhibits a rigid, crystalline long-range order or a flexible, amorphous long-range disorder. Polymers with mr ≈ 50, mm (rr) = 60–79, mm (rr) = 80–89, and mm (rr) ≥ 90

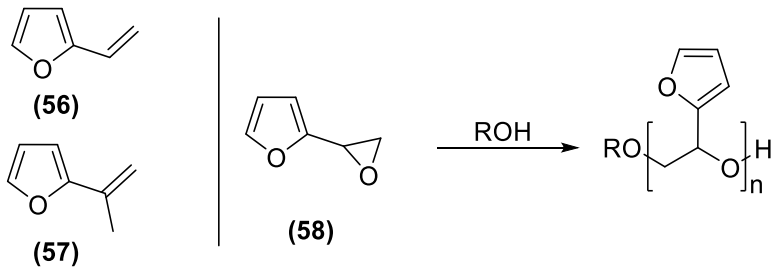
are arbitrarily termed atactic, iso-rich (syndio-rich) atactic, isotactic (syndiotactic), and highly isotactic (highly syndiotactic) polymers, respectively.[52]



Furfuryl methacrylate **(55)**

Scheme 1.6: Organo anionic polymerisation of furfuryl methacrylate by the superbase ^{t}Bu-P$_4$

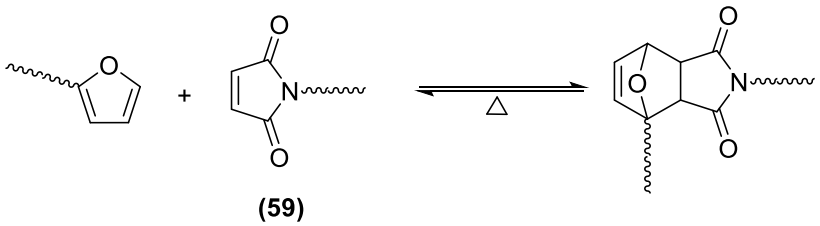
2-Alkenylfurans (2-vinylfuran **56** and 2-isopropenylfuran **57**) are readily activated by even the mildest cationic initiators because of their pronounced nucleophilic character. The anionic polymerisation of 2-furyloxirane **58** is possible due to the high reactivity of the oxirane ring towards strong nucleophiles.[44] Mild nucleophiles such as amines, alcohols or even water were found to propagate slow bulk polymerisation of **58** to produce a polymer with a degree of polymerisation as high as 50 (Scheme 1.7).[44]



*Scheme 1.7: Anionic polymerisation of 2-furyloxirane **58** in the presence of a weak nucleophile (alcohol) as initiator.*

Undoubtedly, the most significant contribution to furan polymers in recent studies is related to the application of the click Diels–Alder (DA) reaction to step-growth polymerisations involving monomers incorporating both furan (diene) and maleimide **59** (dienophile) functions (Scheme 1.8).[26,54] This combination is particularly suited to synthesising macromolecular

materials that can be readily recycled, possess self-mending properties and can be converted into heat-resistant macromolecules by turning the thermally sensitive DA adduct into an aromatic structure.[55] The DA reaction responsible for this reversible growth is shown in Scheme 1.8, where the forward reaction giving the DA adduct predominates up to about 60 °C. In contrast, the equilibrium is heavily shifted in favour of the retro-DA (rDA) reaction that deconstructs the couplings above about 110 °C because at higher temperatures, the system gains more entropy (disorder) by breaking down the Diels-Alder adduct into its individual components, making the reverse reaction thermodynamically more favorable.



(59)

Scheme 1.8: The Diels–Alder equilibrium between furan and maleimide end groups in a stepwise macromolecular synthesis

The exploitation of bifunctional furan-based monomers derived from 5-hydroxymethylfurfural (HMF), particularly 2,5-furandicarboxylic acid (FDCA), has gained significant attention as a sustainable heterocyclic alternative to terephthalic acid. FDCA serves as a versatile platform for the preparation of environmentally friendly polymers, such as polyesters[50] and polyimides[52], which offer a substantially reduced environmental impact. Notably, the synthesis of poly(butylene 2,4-furandicarboxylate) has been demonstrated, showcasing promising properties, including excellent gas barrier performance, thermal stability, flexibility, and toughness.[55]

1.3.6 Terpenes and Terpenoids

Terpenes and terpenoids are components of essential oils that are derived from plants and some animals.[56] Most terpenes are isolated in the largest quantities from turpentine and citrus peel oil.[56] Turpentine is abundant, inexpensive and does not directly compete with food sources, and therefore, it is an ideal source of building blocks for many applications. The composition of turpentine depends on the tree's age and species, among other factors.[56]

Terpenes are recognised for their crucial roles in various industrial applications, with a rich history in flavouring, fragrances, solvents, and even traditional medicine.[56] Recently, their application as monomers or precursors for monomers has gained considerable attention. The fact that these materials can be obtained from waste streams of industries that already operate on a large scale is a significant advantage. This ensures the supply of these materials is plentiful and available at a meagre cost. In addition, the most common method of disposing of these waste streams is incineration ‑ therefore, using these species as renewable feedstocks for bioplastics has a significant positive environmental impact.[56] The best-known example of polyterpene is probably natural rubber. More than 10 megatonnes are produced annually, and the main constituent is polyisoprene. Other terpenes are being investigated as monomers for polymer production, although on a much smaller scale.

These include turpentine, which is extracted from pine trees and is composed mainly of α-pinene **(6)** (45–97%) and β-pinene **(7)** (0.5–28%), limonene **(8)**, and smaller amounts of other non-polar monoterpenes (isoprene **60**) (Figure 1.12). Worldwide production of these monomers is modest: in 2013, about 0.3 kilotonnes of turpentine and about 0.7 kilotonnes of limonene were produced. Commercially available polymer resins from these terpenes already exist.[57]

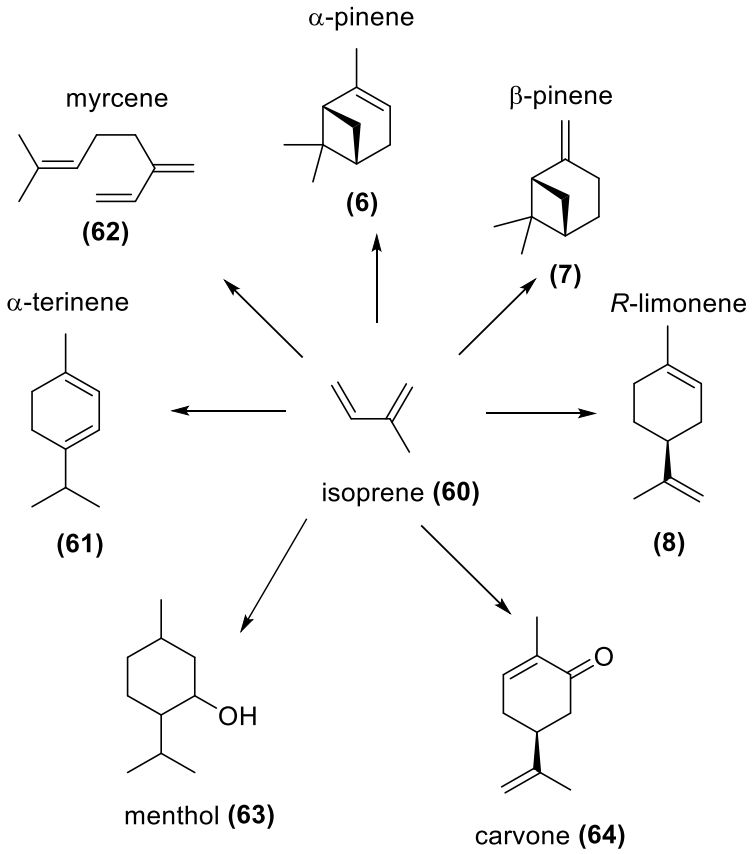


Figure 1.12: Common monoterpenes, which are characteristic of comprising two units of isoprene.

Monoterpenes are particularly diverse structurally due to the presence of numerous stereogenic centres and the many oxygenated compounds that can easily be generated from the basic skeletons. The variety of the compounds in the terpenes platform give rise to a variety of polymers with different desirable properties. Some common terpenes are limonene **(8)**, α-terpinene **(61)**, myrcene **(62)**, α-pinene **(6)** and β-pinene **(7)** (Figure 1.12). They are the most widely studied for polymerisation applications. Oxygenated derivatives, including menthol **(63)**, carvone **(64)** and others, including cyclic terpene alcohols, can also be derived from turpentine.[57]

Limonene (**8**) is the third most prevalent terpene found in turpentine, yet it is primarily concentrated in citrus peels, which can make up more than 90% of the composition. It is also found in over 300 different plant species. Additionally, limonene is created as a secondary

product from the citrus fruit industry; notably, the (*R*)-enantiomer is a significant waste product, generated at approximately 70,000 tonnes annually.[58] The terpenoid carvone (**64**) is found naturally in spearmint and caraway oils, occurring in concentrations as high as 80%. Nevertheless, carvone is typically produced synthetically through the oxidation of limonene, allowing for significant quantities to be sourced ethically and efficiently from the juicing industry. In a similar vein, the terpenoid menthol (**66**) can be synthesised from β-pinene, which can be obtained as a byproduct of the Kraft process used in the paper industry. Geraniol is also important in the biosynthesis of other terpenes. For example, myrcene **(62)** and ocimene are formed by dehydration and isomerisation of geraniol.[59] Geraniol is a monoterpenoid with an alcohol. It is the primary component of citronella oil and a primary component of rose oil.[59]

In the last few years, much more effort has been dedicated to using limonene oxide (LO) (Figure 1.13). The two enantiomers of limonene can be sourced from different natural origins.

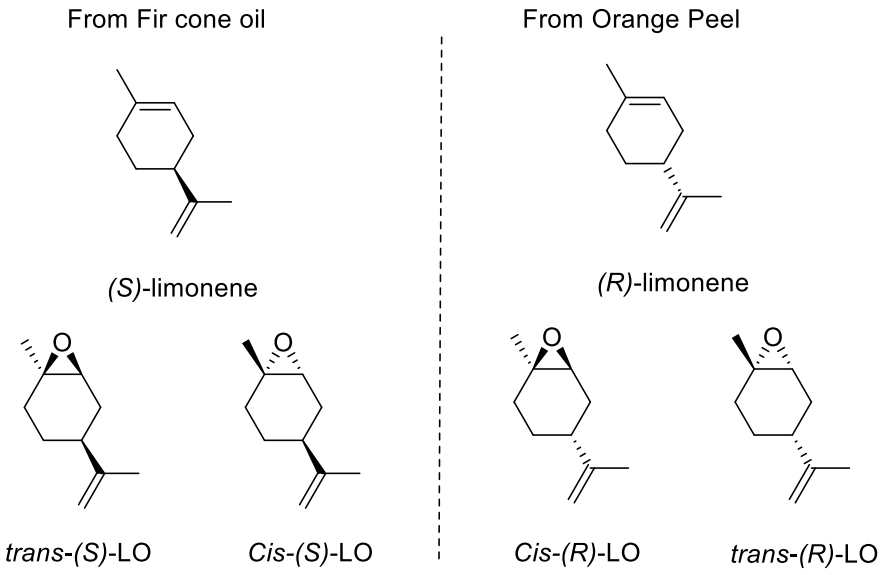


Figure 1.13: Structure of limonene enantiomers and limonene oxide stereoisomers.

For instance, (*S*)-limonene is found in fir cone oil, while (*R*)-limonene is predominantly found in orange peel. Performing epoxidation on either enantiomer results in a mixture of cis and

trans products. Since the extraction of (*R*)-limonene is more economically viable, (*R*)-LO tends to be less expensive, with a *cis:trans* ratio of approximately 46:54.[60] The biotransformation of the α- and β-pinene has been performed since the 1950s to obtain compounds of interest for cosmetics and cleaning product industries. More than twenty compounds were prepared via that route. The oldest reports describe only the biotransformation of α-pinene, for example, the use of Aspergillus niger to produce d-verbenone, d-cis-verbenol, and d-trans-sobrerol. Serratia marcescens has also been used for the oxidation of α-pinene for the production of trans verbenol (majority compound), verbenone, and trans-sobrerol.[61] These chemical modifications inspired organic chemists to use terpenes as novel monomer precursors. As a result, the organic modification of terpenes for synthesising new bio-based polymers is a subject covered by serval recent reviews.[62-64]

The main drawback of terpenes is their direct polymerisation tends to yield low molecular weight polymers, which limits their mechanical performance.[56] It is possible to achieve considerably higher molecular weights through a cationic polymerisation of β-pinene followed by hydrogenation. The resultant polymer displays thermal and mechanical properties comparable to those of polymethyl methacrylate, and the material also shows high optical transmittance.[56]

In general, to utilise terpenes in polymer synthesis, two main ways are used; either

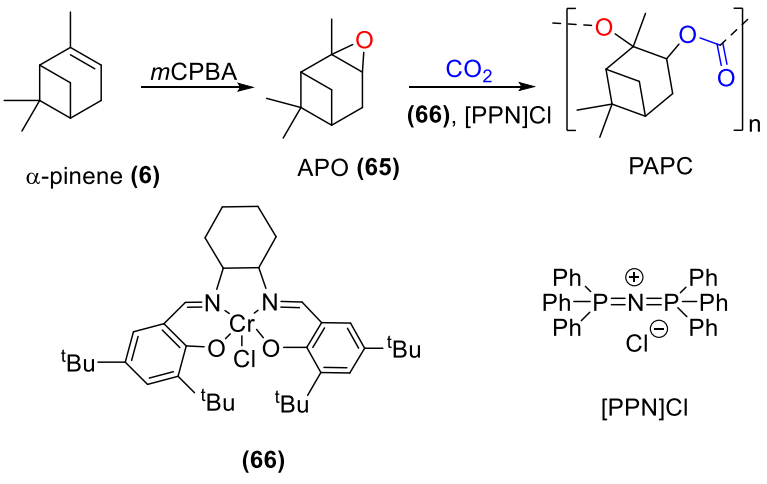
1. convert terpenes into different monomers via chemical reactions to introduce further functionality into the molecules, which would allow polymerisation processes to occur more reliably or
2. direct copolymerisation of the terpenes with fuel-derived monomers such as methyl methacrylate, styrene, etc.

1.3.6.1 Polymers from Terpenes

Despite the enormous and increasing attention for selecting new, cheap, renewable feedstock for sustainable polymer production, terpene use remains relatively unexplored. Besides terpene-based polyolefins, which have matured substantially, recent developments have also shown exciting progress in fabricating other polymers (polycarbonates, polyesters, and polyamides).[65]

1.3.6.1.1 Polymers from α-pinene and β-pinene

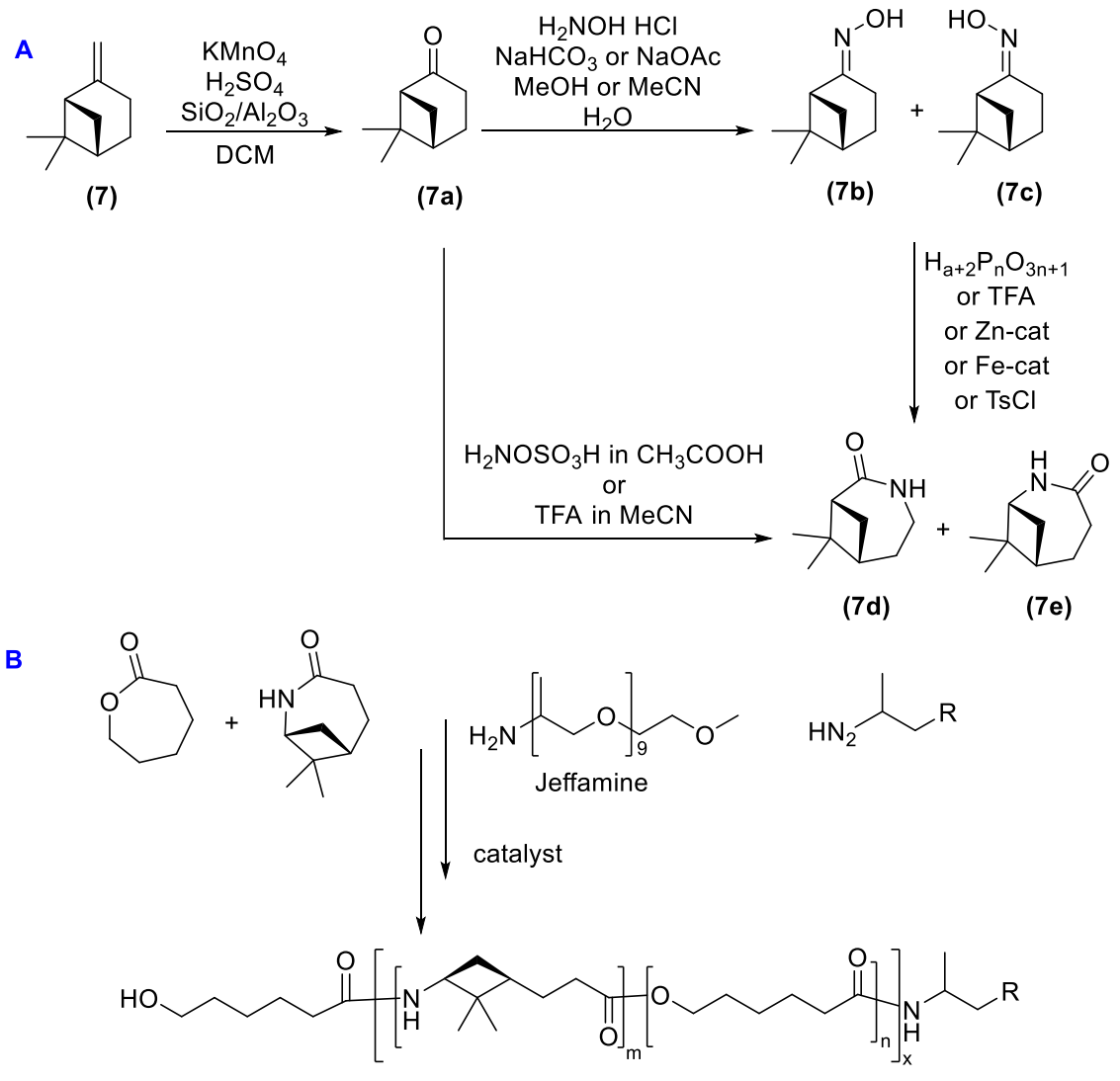
Epoxidation of α-pinene **(6)**, leads to the formation of α-pinene oxide **(**APO **- 65)** (Scheme 1.9). To date, the only example of a synthesis of poly (α-pinene carbonate) is based on ring-opening co-polymerisation (ROCOP) of **65** and CO_2 promoted by the binary catalyst CrIII(salen) complex (**66**) /bis-(triphenylphosphine)iminium chloride ([PPN]Cl).[66]



Scheme 1.9: Synthesis of poly(α-pinene carbonate), from α-pinene, and structures of CrIII(salen) complex and [PPN]Cl. mCPBA stands for meta-chloroperbenzoic acid.

Although β-pinene occurs less frequently than α-pinenes, their exocyclic double bond is located more favorably for further synthesis. β-pinene-based polyesteramides were developed through synthesising β-pinene lactam by oxidising β-pinene (**7**) to nopinone (**7a**) first. For the

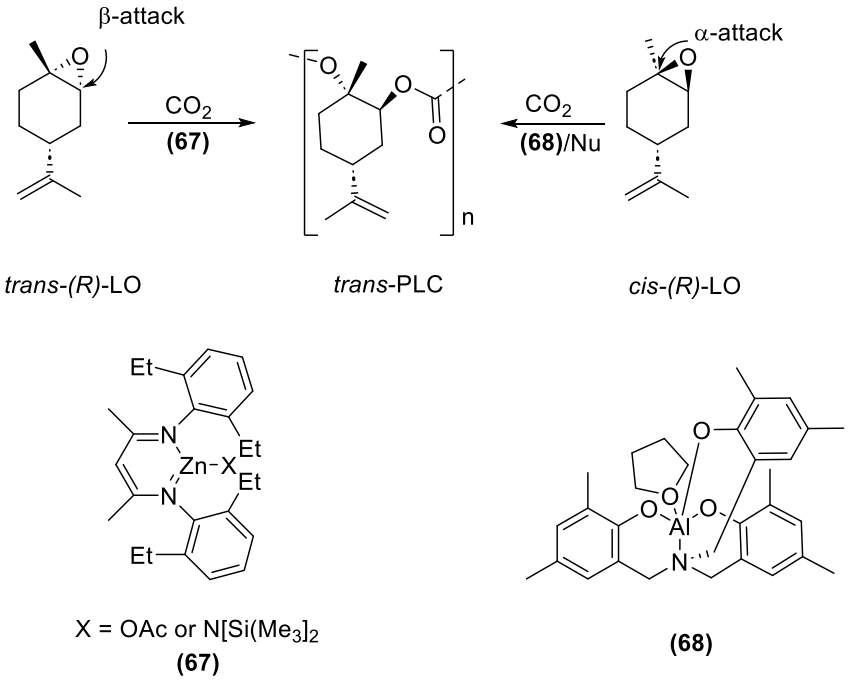
further reaction to the lactams (**7d**, **7e**), two reaction routes are possible: the two-step reaction in which two regioisomeric oximes (**7b**, **7c**) are formed as intermediate products, and the one-step reaction with trifluoroacetic acid (TFA) or hydroxylamine-O-sulfonic acid (HOSA). The corresponding overall reactions are depicted in Scheme 1.10 A. The lactam is then polymerised with ϵ-caprolactone by means of Sn-, Zn- or P-catalyst to the pinene based polyesteramide (Scheme 1.10B).[67]



Scheme 1.10: A) Overview of different synthesis routes of the lactams 7d, 7e and B) its polymerisation.

1.3.6.1.2 Polymers from Limonene

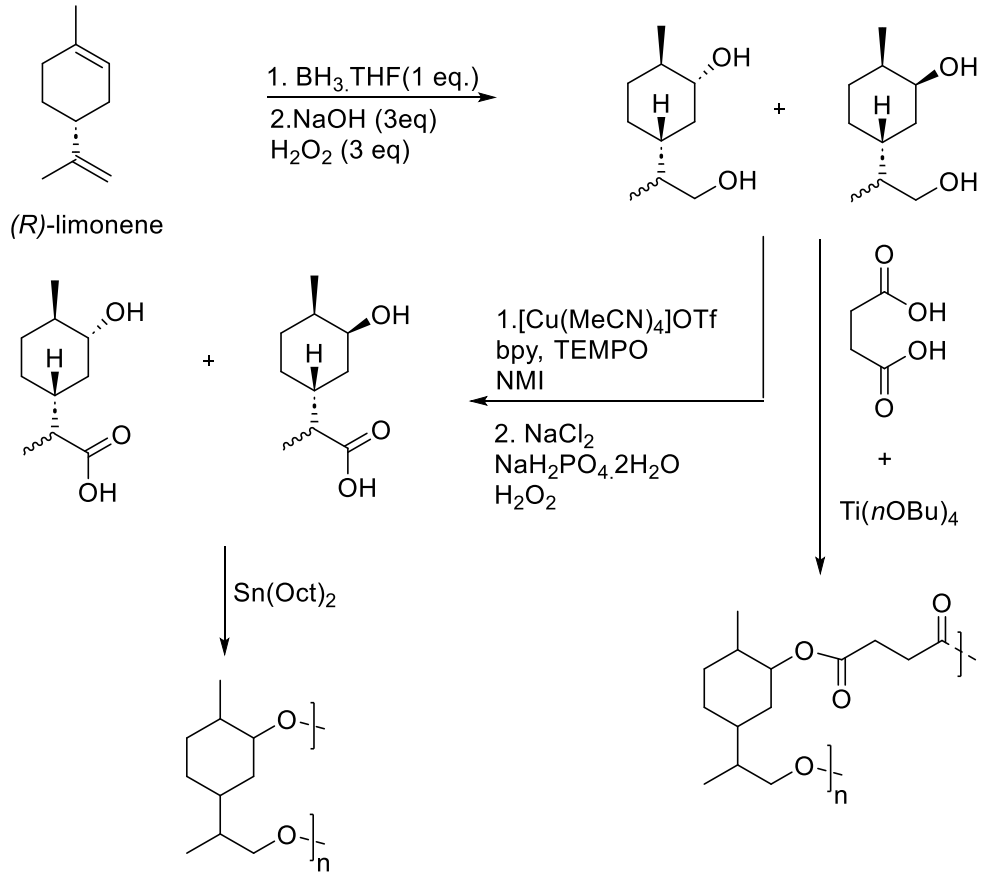
The use of limonene oxide revealed the possibility to obtain functional polycarbonates and furthermore can be synthetically post modified to obtain different materials covering a wide range of properties. Byrne *et al.* described for the first time the copolymerisation of limonene oxide with CO_2 using the β-diiminate zinc complex **(67)** (Scheme 1.11). Starting from *(R)*-LO, poly(limonene carbonate) PLC was produced in a stereoselective fashion (with 98.3% trans configured repeat units) under mild conditions (25 °C, 6.9 bar of CO_2). End-of-life disposal and polymer reuse are critical to sustainable polymer development.[65,68] In this context, the stability of poly(limonene carbonate) PLC in a composting setting has been well established. However, further studies are needed to assess the biodegradation potential of PLC and its derivatives. Li *et al.* reported that depolymerisation of hydroxyl-terminated PLC can be achieved using a relatively simple catalyst (TBD, 1,5,7- triazabicyclo[4.4.0]dec-5-ene) which at high temperature allowed the selective re-formation of the initial limonene oxide monomer through a back-biting mechanism.



Scheme 1.11: Preparation of trans-PLC from trans-(R)-LO and cis-(R)-LO using catalysts.[65, 68]

Such controlled depolymerisation could set the basis for efficient PLC recycling and sustainable material solutions based on a renewable building block.[68]

In the case of polyesters, the main driver has so far been identifying alternatives for polycaprolactone (PCL).[65] Positive outcomes in this area have been reported using various terpenes including (-)-menthol, (+)-β-pinene, and carvone. Additionally, the structural rigidity provided by (bi)cyclic terpene frameworks has enabled the development of polyesters with characteristics akin to poly(ethylene terephthalate) PET or with very high glass transition temperature (T_g) values when combining terpene-based anhydrides and epoxides.[65] Thomsett *et al. 2019* reported the synthesis of limonene-based diols and hydroxy-acids (Scheme 1.12).

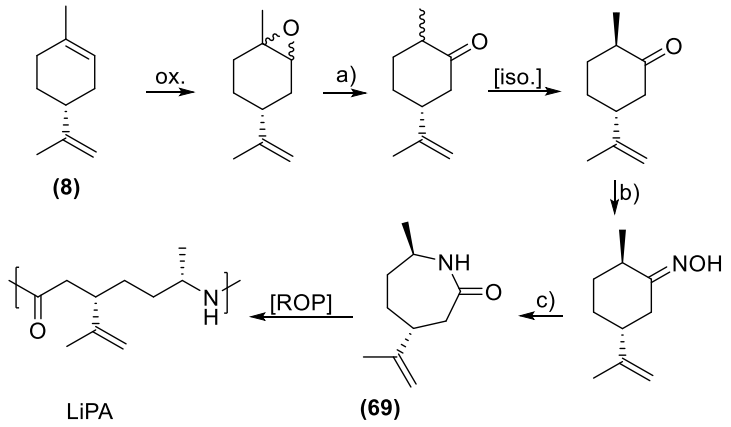


Scheme 1.12: Synthesis of limonene-based diols and hydroxy-acids and their polycondensation reactions.

Limonene was easily converted into diols by a hydroboration-oxidation sequence. Three methods were utilised to convert these diols into hydroxy-acids, and they were classified by a green chemistry metrics evaluation.[69] The simplest approach involved the two-step, chemo-selective oxidation of the primary alcohol to form a carboxylic acid. Diol derivatives underwent copolymerisation with succinic acid using different Lewis acidic catalysts to produce a polymer (Scheme 1.12). Notably, M_n values of up to 30 kDa were obtained using titanium tetra-n-butoxide [$Ti(OnBu)_4$], and T_g values between −7 and 23 °C were observed. The depolymerisation of polymer regenerating the initial diols was also demonstrated under basic conditions.[69]

The preparation of polyurethanes from terpenes remains underexplored mainly, with the only examples known being based on limonene.[70,71] Similar to polyurethanes, few examples of terpene-based polyamides (PAs) have been reported to date, with polycondensation and ROP approaches. On the other hand, semi-crystalline aliphatic polyamides, exhibiting better thermal properties than traditional polyamides like Nylon-6, have been developed from structurally robust precursors such as nopinone, and α-pinene.[65] Recently, limonene lactam **(69)**, a novel biobased monomer for preparing sustainable polyamides via ROP, was synthesised (Scheme 1.13).[72] Limonene lactam possesses an iso-propylene and a methyl side group; thus, stereocenters pose special challenges and requirements for synthesis and polymerisation. Still, it can generate novel polymers with unique properties, e.g., functionalisability. Various initiators and conditions in bulk ROP to limonene polyamides were tested. $Zn(OTf)_2$ and $Zn(ClO_4)_2$ as initiators and catalysts were found to be unsuitable. $Zn(ClO_4)_2$ showed low conversion and yield despite relatively high amounts of catalyst and $Zn(OTf)_2$ showed high conversions and acceptable yields, but also many side reactions. Other catalysts, $ZnBr_2$ and

$Fe(ClO_4)_2$ showed hardly any difference in terms of conversion (>99%) and yield (>90%) but differed significantly in reaction time (19 and 4 h).



*Scheme 1.13: Synthesis of limonene lactam and its polyamide from limonene oxide via ketone 2 and oxime 3. a) $ZnBr_2$, EtOAc or $Fe(ClO_4)_2$, cy-Hex; b) NH_2OH*HCl, NaOAc, EtOH:H_2O; c) NaOH, TsCl in MeCN or TFA, $AlCl_3$. ROP with NaH, NHCs, DPP, H_3PO_4, P4-tBu or HCl.*

The resulting polymerisation produced polymers of relatively high T_{gs} up to 100 °C, thermal decomposition temperature T_{ds} up to 423 °C, and no detectable melting temperature T_m.[72]

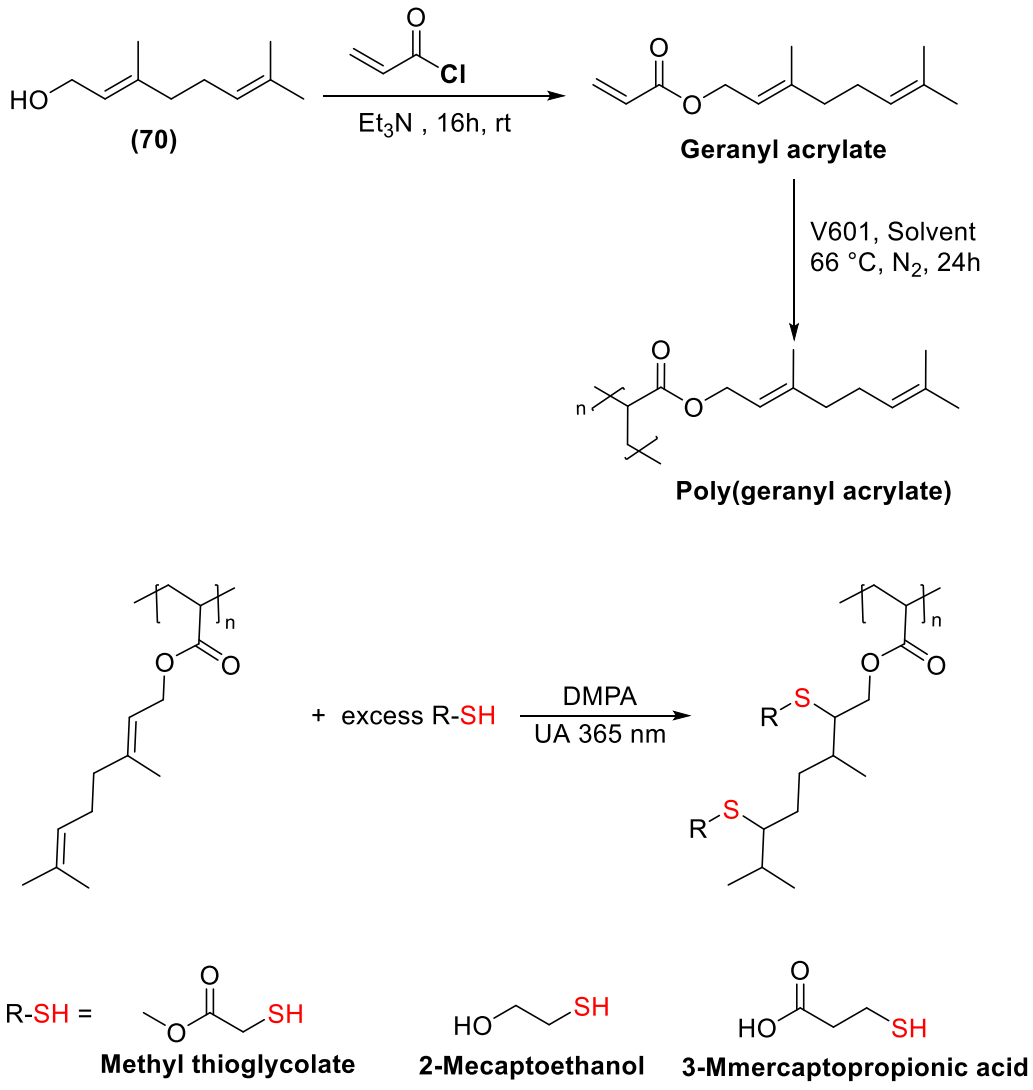
1.3.6.1.3 Polymers from Geraniol

Geraniol is a naturally occurring monoterpenoid alcohol predominantly found in essential oils such as rose, citronella, and palmarosa. Beyond its widespread use in fragrances and flavorings, geraniol has gained attention as a renewable monomer for polymer synthesis, aligning with the growing emphasis on sustainable and bio-based materials.

Structurally, geraniol consists of a linear chain with two double bonds and a terminal hydroxyl (-OH) group, providing multiple reactive sites for chemical modification. The hydroxyl group can undergo esterification or etherification, enabling its incorporation into polymer backbones or side chains. Meanwhile, the conjugated double bonds allow for reactions such as epoxidation and thiol-ene click chemistry, expanding the range of polymer architectures that can be derived

from geraniol. These modifications make geraniol a versatile building block for the development of advanced functional polymers.[73]

The hydroxyl (-OH) group in geraniol can be modified to enhance its polymerisation capabilities, particularly for step-growth polymerisation. Geraniol can be esterified with carboxylic acids or acid chlorides to form acrylates, methacrylates, or polyesters.



Scheme 1.14: Synthesis of geranyl acrylate, then FRP of geranyl acetate in three solvents, the functionalization of poly (geranyl acrylate) with various thiols through a photoinitiated thiol-ene reaction.

Geranyl methacrylate (GMA) was synthesised by the esterification of geraniol with acryloyl chloride in the presence of triethylamine. Both free radical polymerisation and Cu-mediated reversible deactivation radical polymerisation (RDRP) were employed to synthesise poly(geranyl acrylate) with various molecular weights, using both conventional petro-derived organic solvents and bio-based, renewably sourced solvents. Furthermore, poly(geranyl acrylate) underwent photoinduced thiol-ene reactions, utilising different thiols with a variety of functional groups, expanding its potential for functional polymer applications (Scheme 1.14).[74]

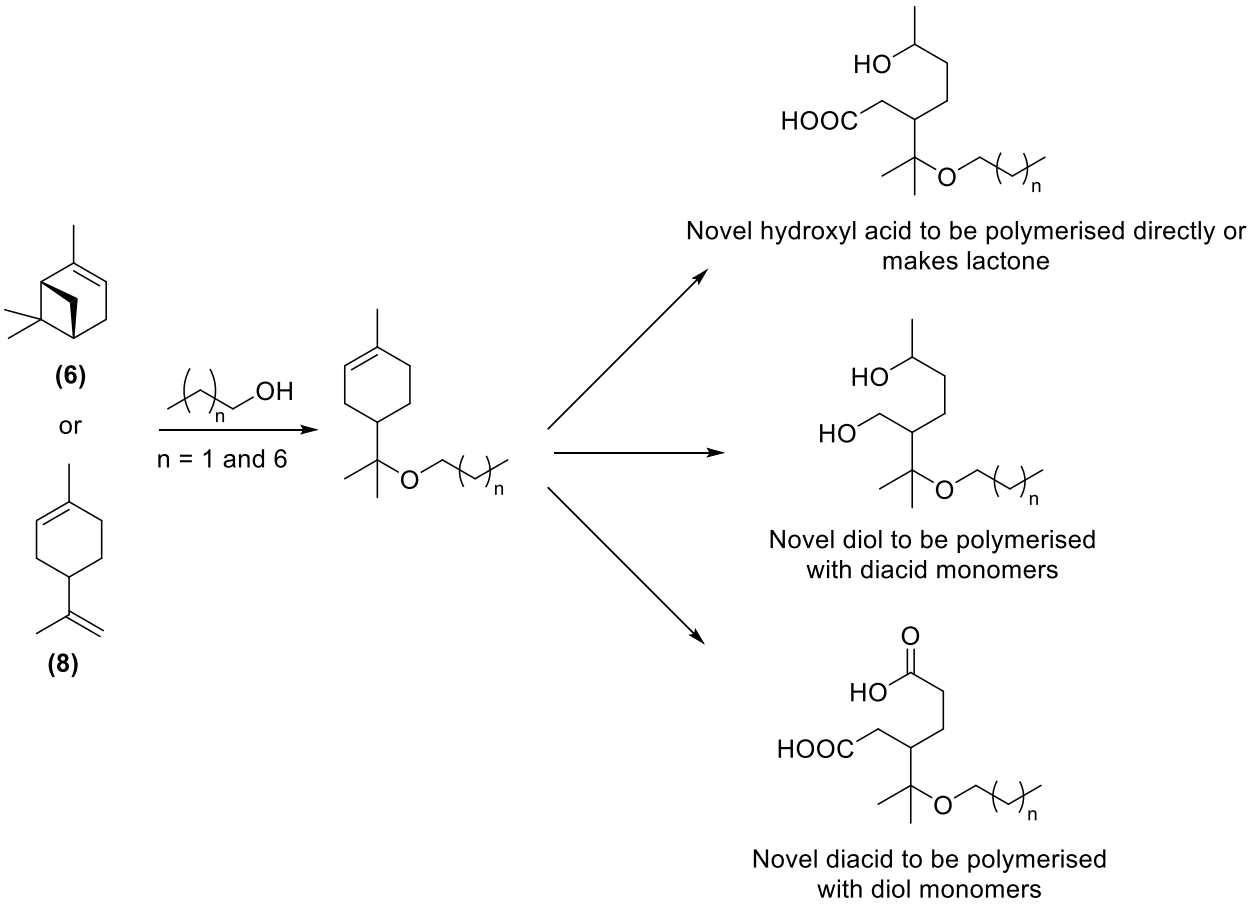
In conclusion, terpenes are widely available from low-cost, renewable biological sources (such as pinene and limonene) and do not compete with the food supply chain. Their olefin groups provide numerous opportunities for chemical modifications, including addition and epoxidation reactions, enabling the synthesis of tailored materials with specific mechanical, thermal, optical, conductive, or medicinal properties. Furthermore, the presence of multiple double bonds with varying reactivities within the terpenoid structure enhances their potential for further post-functionalization. Additionally, terpenes exhibit remarkable structural versatility—ranging from linear to cyclic and polycyclic frameworks—allowing for the development of novel materials with a broader spectrum of properties than those offered by most conventional monomers used in the polymer industry.

1.4 Aims and Objectives:

In the previous sections, several types of biomass-derived monomers were described. Fundamental advances have been achieved in developing biomass-derived plastics, as discussed. However, there is still a long way to go to attain bio-based plastics matching the properties and uses of petrochemical-derived polymers. Therefore, finding promising bio-

based monomer candidates is of utmost significance. Terpenes have become one of the most promising candidates for acting as building blocks in synthesising polymers out of all the compounds obtained from biomass.

This project aims to synthesise novel monomers derived from the most common biomass chemicals, such as limonene, α-pinene, β-pinene, geraniol, and furfural.

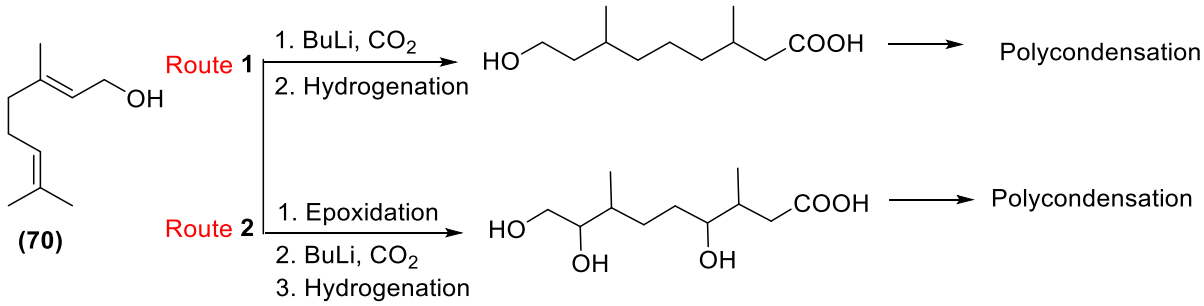


Scheme 1.15: Proposed synthetic route to convert limonene and α-pinene into novel monomers

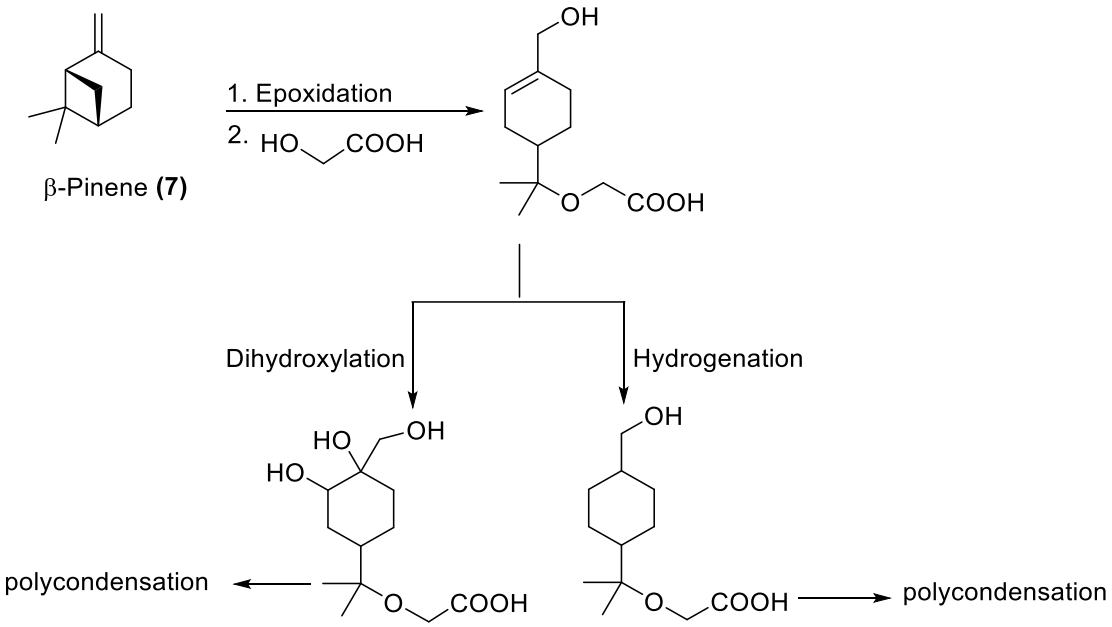
Furthermore, some of these novel monomers will be polymerised using suitable polymerisation methods: polycondensation, ring-opening polymerisation, and radical polymerisation.

Various synthetic methodologies will be explored to generate a wide range of diacids and diols, which can then be polymerised via step-growth (or condensation) polymerisation to make

novel polyesters (Scheme 1.15). Geraniol **(70)** could be converted into either lipophilic or hydrophobic hydroxy acids monomers by using lithiation/carboxylation techniques either before (route 1) (Scheme 1.16) or after epoxidation (Route 2). The potential product of route two could be polymerised and depolymerised in acidic media to form a 5-ring lactone.



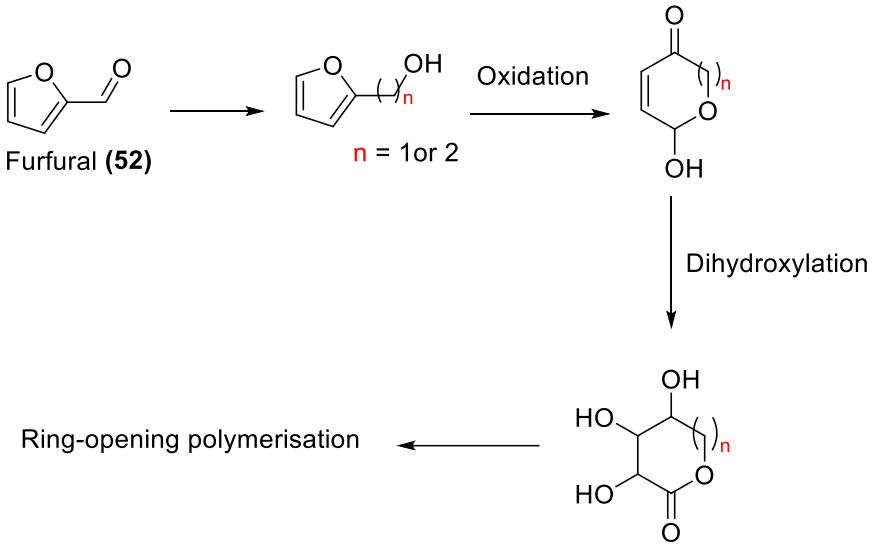
Scheme 1.16: Converting geraniol into lipophilic and hydrophilic hydroxy acids to be used as monomers to make polyesters via polycondensation



Scheme 1.17: Converting β-pinene into hydroxy acids to be used as monomers to make polyesters via polycondensation

Alcohol-carboxylic acid monomers can also be made by fragmentation or addition to β-pinene oxide. Again, lipophilic and hydrophobic monomers/polymers can be made.

Also, the presence of α-oxygen will enhance the reactivity of the ester linkage making it more hydrolysable (Scheme 1.17).



Scheme 1.18: Converting furfural into novel 6 or 7-member ring lactones where they can be polymerised via ring-opening polymerisation to make hydrophilic polyesters.

Furfural can also prepare novel 6 or 7-membered ring lactones that could be polymerised via ring-opening polymerisation to make hydrophilic polyesters (Scheme 1.18). The hydroxyl groups of these rings could be protected before carrying out living ROP. Then they can be deprotected post-polymerisation.

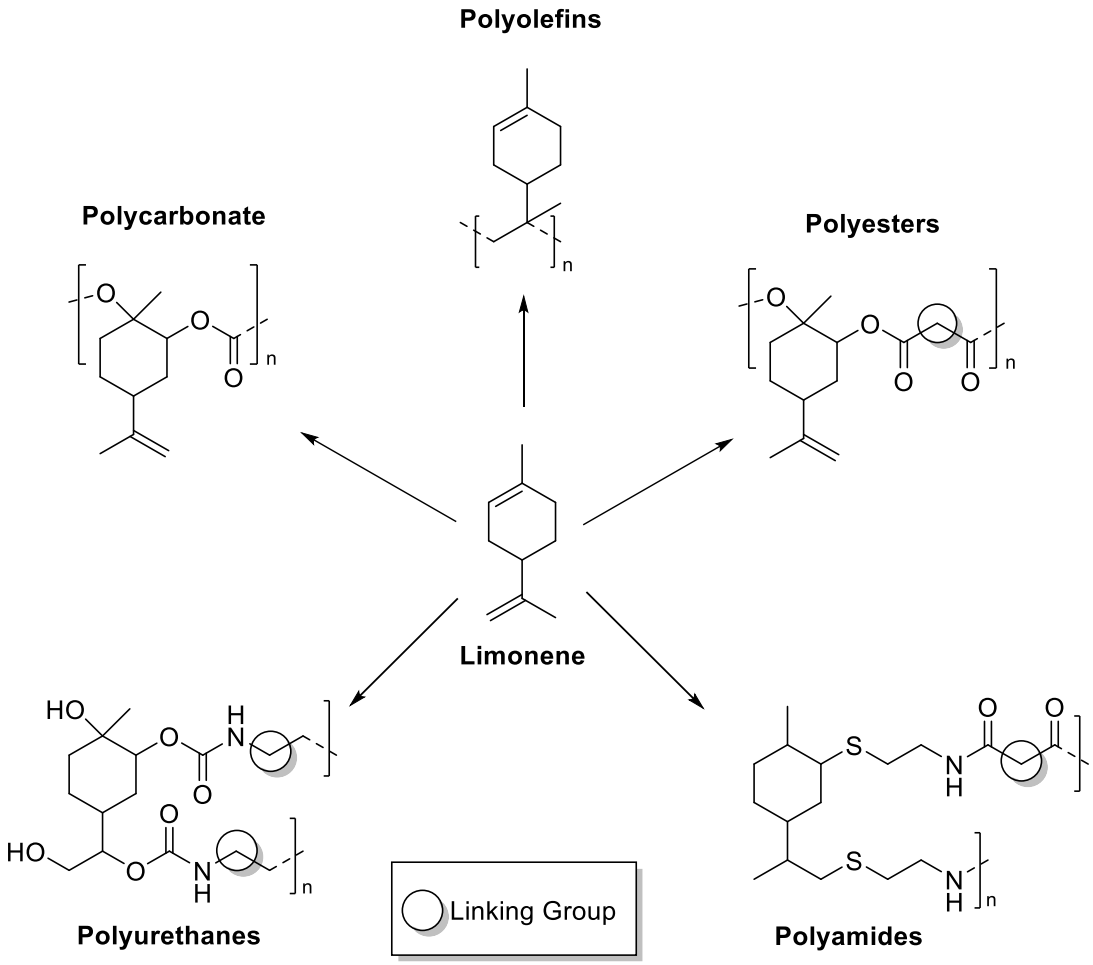
Chapter Two:

2. Monomer Derivatives from Terpenes

Terpenes or terpenoids, a large class of diverse biological compounds derived from isoprene, are gaining attention in polymer preparation due to their natural abundance and desirable properties. While Terpenes are pure hydrocarbons made of isoprene units, Terpenoids are oxygenated or chemically modified terpenes. The chemical structures of many terpenes, with moieties such as (conjugated) double bonds, hydroxyl or carboxyl groups, can be utilised in monomer, polymer preparation and/or functionalisation.[75] Importantly, using naturally abundant and biorenewable terpenes to make functional polymers meets sustainable development needs and significantly reduces our dependency on mineral oil. This reduction in our reliance on non-renewable resources, coupled with the desirable properties of terpene entities, such as biodegradability, lipophilicity, bioactivity, and crystallinity, makes the resulting polymers or polymer conjugates promising for a wide range of applications, from biotechnological to optical materials.[75]

In this context, monomers based on bio-derived terpenes are gaining increasing interest. Polyisoprene, which is a key component of natural rubber, has been recognised for over a hundred years, and other terpenes, such as pinene, limonene, pirocarvone, myrcene, alloocimene, ocimene, and farnesene, have also been used in the preparation of polyolefins.[75-77] The diverse applications of these terpene-based monomers, from traditional uses in rubber to innovative applications in advanced materials, underscore the exciting potential of this research.[75-77]

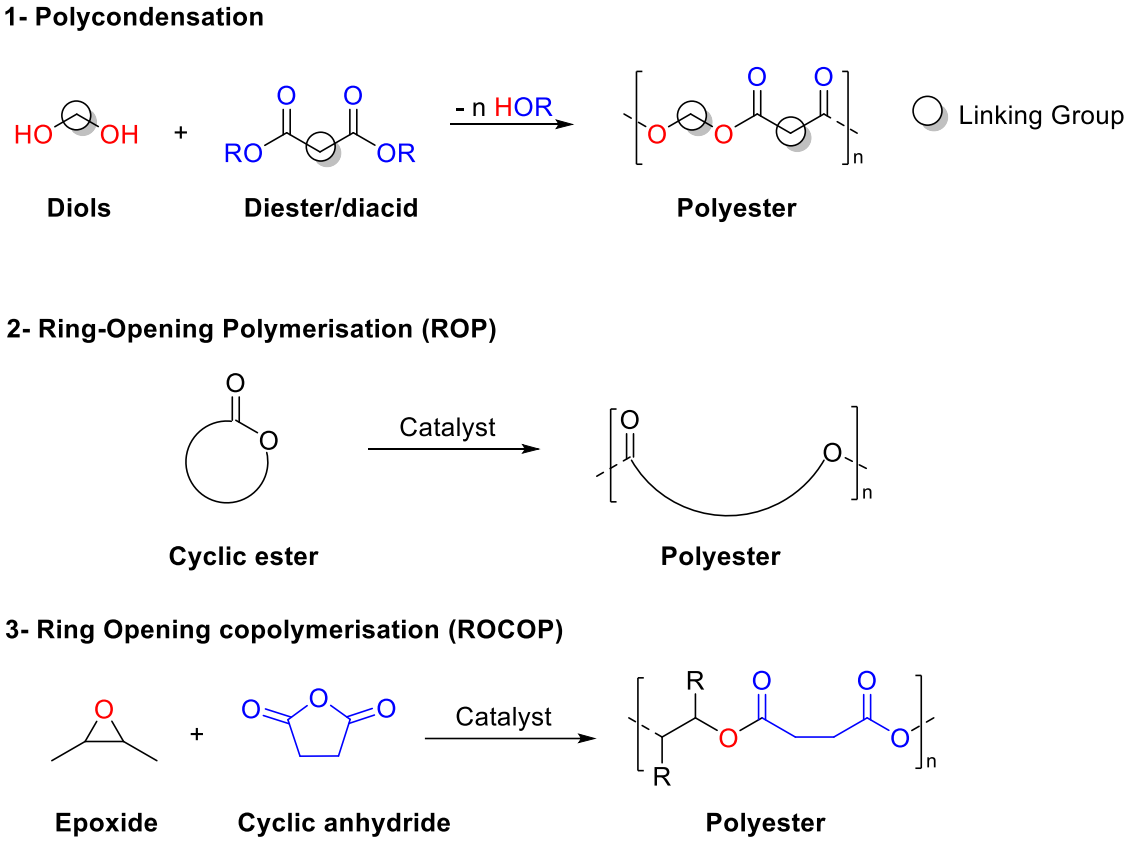
Limonene, a commercial monoterpene isolated from citrus fruits, has a terpene structure comprising two separate double bonds that can be readily altered, for example, through epoxidation or thiol-ene click reactions. These characteristics, along with the accessibility of this terpene feedstock, have enabled the creation of structurally varied polymeric materials, highlighting limonene as a promising platform molecule (Scheme 2.1).[64]



Scheme 2.1: Polymer diversity created from limonene.

Aliphatic polyesters (APEs) are considered a highly promising category of sustainable polymers due to their overall biocompatibility and ease of hydrolytic degradation. APEs can be synthesised through the polycondensation of diols with dicarboxylic acids or esters, the ring-

opening polymerisation (ROP) of cyclic esters, and the ring-opening copolymerisation (ROCOP) of epoxides with cyclic anhydrides (Scheme 2.2).[64]



Scheme 2.2: The three possible synthetic routes of polyesters: polycondensation, Ring-Opening Polymerisation and Ring-Opening Copolymerisation.

2.1 Aim and Objectives:

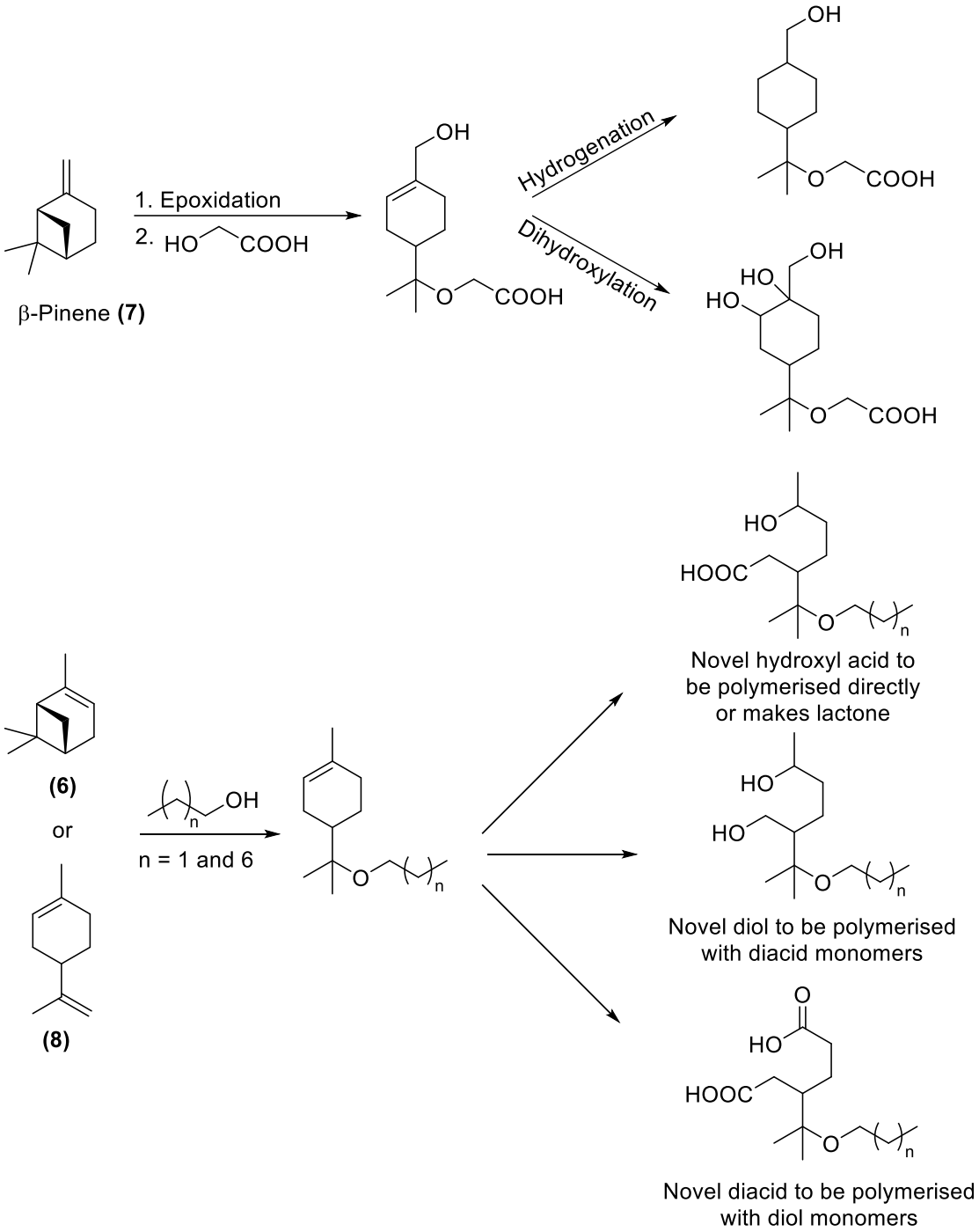
This chapter details our investigations into the synthesis of novel derivatives from limonene, α- and β-pinene and geraniol as polymer precursors. These compounds, along with β-pinene and geraniol, contain at least one alkene group, which can be functionalised through alcohol addition, oxidation, or dihydroxylation (as illustrated in Scheme 2.3). The resulting derivatives have the potential to serve as valuable chemical intermediates for various applications, including:

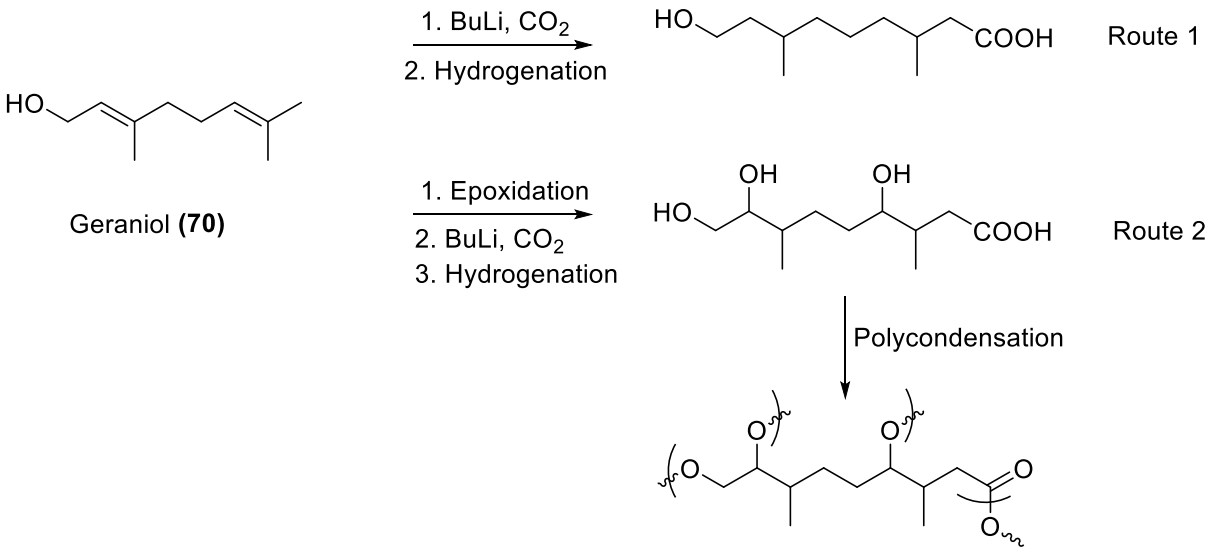
1- monomer precursors to monomers such as lactones, or

2- to be polymerised directly to produce novel homopolymers, or

3- used as conjugates (side or end groups) with other polymers, or

4- copolymerised with other monomers to make novel copolymers.



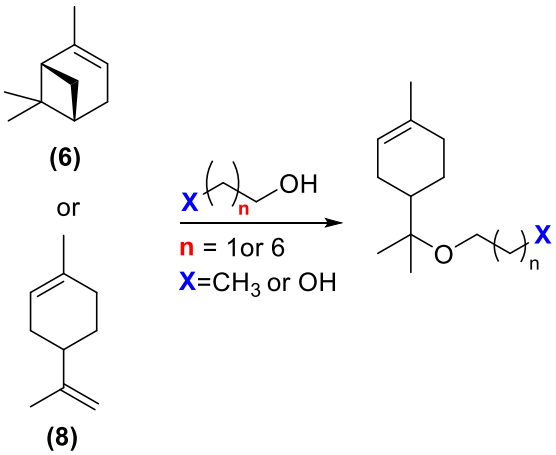


Scheme 2.3: The aim and objectives discussed in this chapter is to convert limonene, α-pinene β-pinene and geraniol into novel polyester precursors.

2.2 Monomers from limonene and α-pinene

2.2.1 Synthesis α-terpenyl derivatives by alcohol addition:

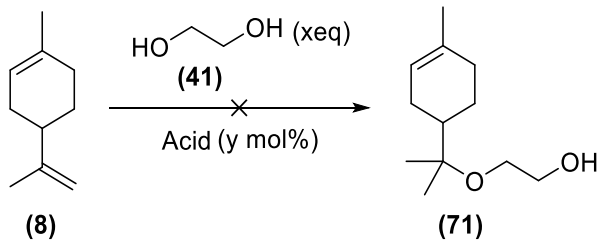
Adding alcohol to limonene and α-pinene will yield compounds with a side group that affects the potential polymer's chemical and physical structures. The length and hydrophobicity of this side chain are key factors in changing the chemical and physical structures of the produced polymer. In this work, we explored the methods of adding relatively short alcohols, such as 1-propanol, and relatively long alcohols, such as 1-octanol (Scheme 2.4).



Scheme 2.4: Synthesis of α-terpenyl derivatives by alcohol addition.

2.2.1.1 Acid-catalysed addition of alcohol to alkene

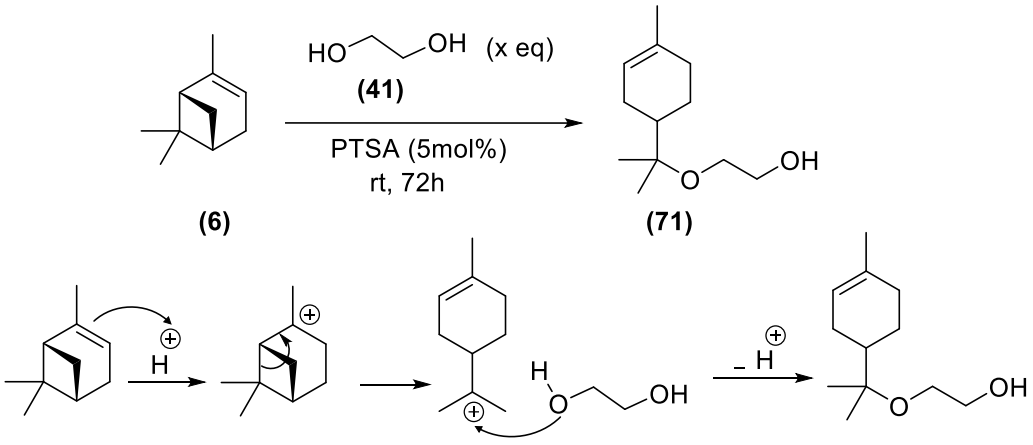
Ethylene glycol (EG) **(41)** produced from biomass is a promising candidate for several new applications. Hence, utilising EG to functionalise terpenes will support sustainability. In the presence of an organic acid such as p-toluenesulfonic acid (PTSA) or triflic acid (TfOH), the alkene group of limonene will act as a nucleophile and attack the proton to form a carbocation. This carbocation will be attacked by the nucleophile (hydroxyl) of the di-alcohol (EG) to produce the desired product (Scheme 2.5).[78] Several attempts were conducted with and without solvents where the time, temperature of the reaction, and reactant equivalents were varied (Table 2.1). However, none of the attempts resulted in the product, as limonene did not react.



Scheme 2.5: The proposed reaction of limonene with ethylene glycol

Table 2.1: The attempts and results of reacting limonene with ethylene glycol.

Entry	Ethylene glycol (x eq)	Acid	Acid (y mol%)	Solvent	Temp. (°C)	Time (h)
1	4	PTSA	5	2-Butanone	25	72
2	4	PTSA	5	Acetone		72
3	2	PTSA	5	-		72
4	4	TfOH	1	1,4-dioxane		96
5	4	TfOH	2			96
6	4	TfOH	1		60	48
6	4	TfOH	2			48
7	2	TfOH	2	-		48

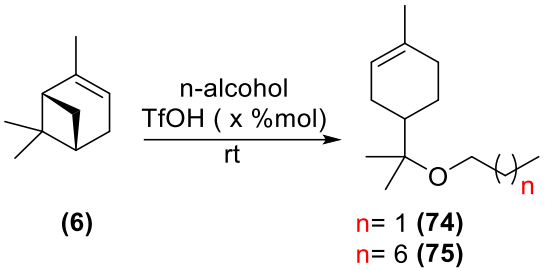


Scheme 2.6: The reaction and mechanism of a-pinene with ethylene glycol to afford the desired terpene derivative.

Table 2.2: The results of a-pinene with ethylene glycol to afford the desired terpene derivative.

Entry	Ethylene glycol (x eq.)	Solvent	Yield (%)
1	4	2-butanone	-
2	4	acetone	10
3	4	-	8
4	2	-	25

On the other hand, when α-pinene was used as the precursor, the desired product was obtained with a relatively low yield (8-25 %) with or without acetone as a solvent at room temperature (Scheme 2.6 and Table 2.2). We believe the release of ring strain promotes this unusual reaction. Having determined that ethylene glycol (EG) yields low efficiency as a functionalising agent, we hypothesised that its relatively electron-poor nature might make it a weak nucleophile. Consequently, we decided to explore alternative alcohol-based agents, such as 1-propanol **(72)** and 1-octanol **(73)** which are more electron-rich, and thus better nucleophiles. α-Pinene **(6)** was treated with 1-propanol and 1-octanol in the presence of triflic acid (trifluoromethanesulfonic acid -TfOH). The results of these experiments are shown in Table 2.3.[79]



Scheme 2.7: Synthesis of α-pinene derivatives by alcohol addition.

Table 2.3: Results of α-pinene alcohol derivatives.

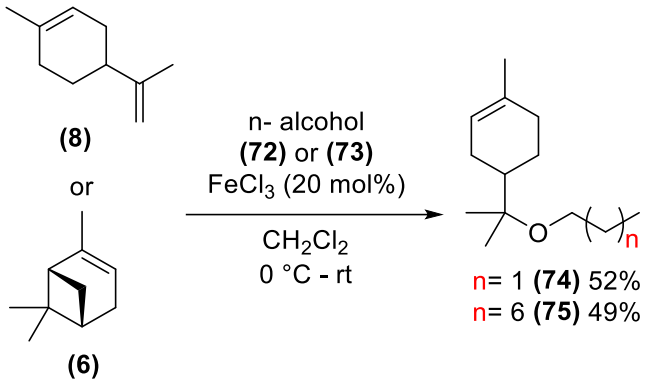
Entry	(x) mol%	n (1 eq.)	Solvent	Time (h)	Yield (%)
1	1	6	DCM	24	15
2	1	6	-	72	31
3	5	6	DCM	18	22
4	5	1	-	72	35
5	5	6	-	72	26

The acid promoted reaction of α-pinene was carried out at an ambient temperature at different hours, both neat and with dichloromethane (DCM) as a solvent. The product was confirmed by ^{1}H NMR. The yield of this reaction varied from 15 to around 35% without side products as subjected by TLC. While increasing the percentage of the catalyst (TfOH) from 1% to 5% reduced the yield slightly (entry 2 *vs* 5 of Table 2.3), leaving the reaction without a solvent for a longer time produced a higher yield (entry 1 *vs* 2). This low yield is probably because of the low solubility of 1-octanol in DCM or low miscibility with *α*-pinene. Using another solvent and carrying out the reaction at elevated temperatures may increase the yield. Due to the low yield of this synthetic route, another method was investigated.

2.2.1.2 Lewis Acid-catalysed addition of alcohol to alkene:

Electron-rich C–C multiple bonds, such as the alkene in α-pinene or limonene, can be activated by metal-based catalysts and undergo functionalisation by heteronucleophiles. The lack of

reactivity of non-activated olefins towards nucleophiles, particularly oxygenated nucleophiles such as alcohols, and their activation by metal-based catalysts was a challenge in synthetic organic chemistry. Iron (III) chloride has recently emerged as a powerful Lewis acid catalyst to perform many useful organic transformations under mild reaction conditions.[80] Moreover, iron salts are inexpensive, easy to handle and environmentally friendly. Yadav *et al.* reported a direct $FeCl_3$-catalyzed hydroalkoxylation of monoterpenes such as α-pinene, β-pinene, and limonene with alcohols under mild conditions to produce a wide range of the corresponding ethers in excellent yields.[80]



Scheme 2.8: Hydroalkylation for Limonene and α-pinene to produce via Lewis acid $FeCl_3$ to produce corresponding ethers (propanol, octanol)

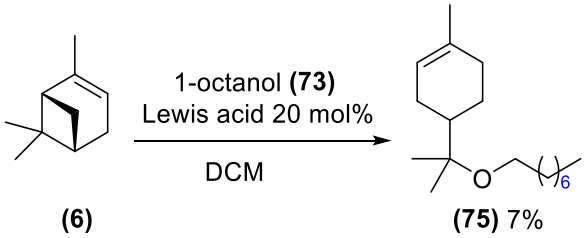
Mechanistically, the reaction may proceed via the activation of alkene by the metal catalyst and subsequent migration of double bond through the opening of the four-membered ring with appropriate alcohol. In general, the regioselectivity was strongly in favour of the Markovnikov-type product. In the case of limonene, the metal chooses the terminal alkene, and the attack of nucleophiles follows Markovnikov's rule.

We carried out this reaction using iron(III) chloride (20 mol%) as a Lewis acid and DCM as a solvent. The yields from α-pinene or *R*-limonene with 1-propanol or 1-octanol were around 50% (Table 2.4). The products were characterised by ^{1}H NMR, IR and mass spectrometry.

Table 2.4: The yield of hydrodealkylation for Limonene and α-pinene via Lewis acid $FeCl_3$ to produce corresponding ethers (propanol, pentanol, octanol).

Entry	Terpene	n	Alcohol	Time (h)	Yield
1	(-)-α-pinene	1	1-propanol	1.3	52%
2	(*R*)-(+)-Limonene	1	1-propanol	1.3	51%
3	(-)-α-pinene	6	1-octanol	2	49%
4	(*R*)-(+)-Limonene	6	1-octanol	3	47%

On the other hand, no reaction or significantly lower yield was noted when α-pinene was used as a precursor with other Lewis acids. First, we noted the iron chloride acids are not dissolved and this may be hampering the reaction. We, therefore, decided to use more soluble Lewis acids (Scheme 2.9 and Table 2.5). These Lewis acids (Table 2.5) efficiently initiated substrate activation through coordination. However, the regio- and chemoselectivities of the reaction varied depending on the specific Lewis acid used, leading to the formation of multiple products.



Scheme 2.9: Hydrodealkylation of α-pinene via three different Lewis acids $FeCl_3$ to produce the corresponding ether.

Table 2.5: The results of hydrodealkylation of α-pinene via three different Lewis acids FeCl3 to produce the corresponding ether.

Entry	Lewis acid	Solvent	Temperature (°C)	Time (h)	Yield (%)
1	$FeBr_3$	DCM	25	8 or 16	7
2	$TiCl_4$	DCM	25	8	-
3	$BF_3.Et_2O$	DCM	25	7	-
4	$BF_3.Et_2O$	DCE	70	4	-

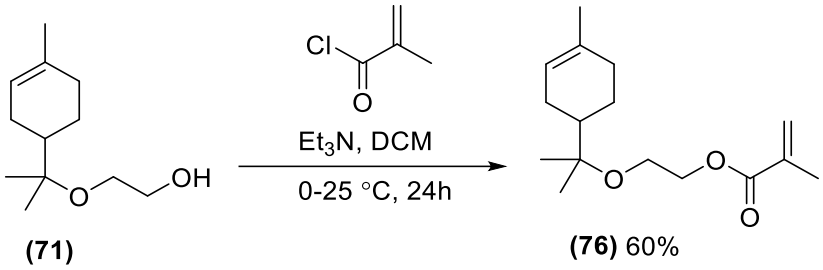
Extending the reaction time to 16 hours did not improve the yield when $FeBr_3$ was used. The reactivity in these transformations relies on a catalytic activation mechanism, where the Lewis acid forms a complex with the substrate at a Lewis basic site. This interaction lowers the LUMO (Lowest Unoccupied Molecular Orbital), facilitating the reaction by enhancing the nucleophilicity of the alcohol. $FeCl_3$ is a stronger Lewis acid than $FeBr_3$ due to chlorine's higher electronegativity compared to bromine.

Among various Lewis acids such as $TiCl_4$, $SnCl_4$ and $BF_3.OEt_2$ tested by Schindler *et al.*, $FeCl_3$ was found to be superior in terms of conversion. When this research group used α-pinene and benzyl alcohol in the presence of $TiCl_4$, $SnCl_4$, $BF_3.OEt_2$ and $FeCl_3$ gave the desired product in 45%, 52%, 65% and 80% yields, respectively.[81] However, in our hands, we did not obtain the desired products with $TiCl_4$ or $BF_3.EtO_2$. These Lews acids are likely co-ordinating the alcohol and stopping its participation in the reaction.

The alcohol derivates of limonene and α-pinene were successfully synthesised using iron (III) chloride as a Lewis acid. Now, the next step is the oxidation of the alkene group to afford diols, hydroxycarboxylic, or dicarboxylic groups suitable for condensation polymerisation.

2.2.1 Couplig the alcohol derivative with methacrylate

Coupling ethylene glycol with α-pinene produced a chemical that has a hydroxyl group which can be functionalised. The reaction of methacryloyl chloride with this hydroxyl group will introduce a double bond that can be polymerised by radical polymerisation (Scheme 2.10). This reaction was carried out with dichloromethane as a solvent and triethylamine as a catalyst. The reaction started at 0 °C and then warmed to room temperature for 24 hours to form the ester in 60% yield.[82]



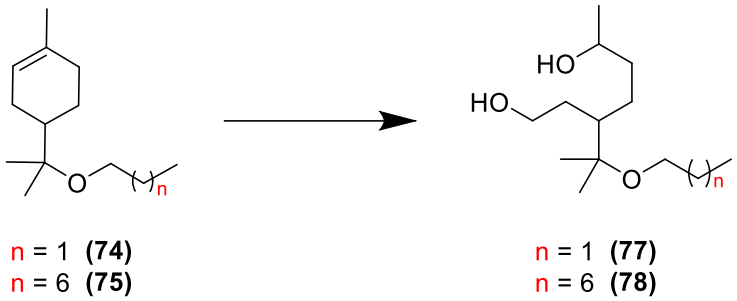
*Scheme 2.10: Introducing a methacrylate group to (**71**) to afford a polymerisable double bond.*

2.2.3 Oxidative cleavage of α-terpenyl derivatives:

The resulting alcohol derivatives of limonene and α-pinene have an alkene group which can be oxidised towards diol, hydroxycarboxylic, or dicarboxylic derivatives. Metal catalysts have been used for the catalytic oxidative cleavage of internal olefins. Expensive and often toxic transition-metal complexes of Ru, W or Os are known to catalyse oxidative cleavage. The well-known Sharpless system uses periodate as the oxidant with $RuCl_3$ in different solvent mixtures.[83] From an economic and environmental perspective, it would be desirable to use catalysts based on cheaper, less toxic and more abundant metals, such as the first-row transition metals. Oxone ($2KHSO_5.KHSO_4.K_2SO_4$) has been used in aqueous acetonitrile to cleave styrene derivatives and cyclic olefins to aldehydes with catalytic amounts of $RuCl_3$. Oxone is an attractive oxidant for alkene oxidation, as it is cheap and readily accessible. Epoxidations with oxone have been reported in water at neutral pH and without organic solvent. Other common solvents for epoxidations with oxone are aqueous acetonitrile or hexafluoroisopropanol. Eventually, the diol intermediates, which can be obtained by hydrolysis of the epoxide or directly formed by cis-dihydroxylation, can be cleaved by periodate to give the corresponding aldehydes or ketones.[83]

2.2.3.1 Toward diol derivatives:

The next step was to convert the resulting α-terpenyl derivates into a diol derivative that can be used as a monomer with another dicarboxylic monomer in condensation polymerisation (Scheme 2.11).



n = 1 **(74)**
n = 6 **(75)**

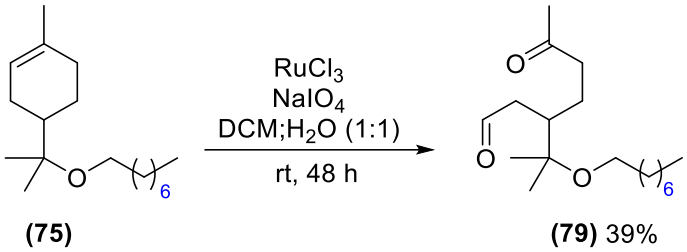
n = 1 **(77)**
n = 6 **(78)**

Scheme 2.11: Dihydroxylation cleavage of α-terpenyl derivatives into diol derivatives

The proposed synthetic route was converting the alkene group into aldehyde-ketone and then reducing these aldehyde-ketone groups into diols. Two synthetic routes were investigated to convert the alkene into aldehyde-ketone groups, which are described below.

2.2.3.1.1 Ruthenium-Catalysed Oxidative Cleavage of Olefins into aldehyde-ketone in one step

Ruthenium complexes have great potential for catalytic oxidation reactions of various compounds. The reactivity of ruthenium complexes can be controlled by its oxidation state and ligands. The highest-valent ruthenium complex is ruthenium (VIII) tetroxide (RuO_4), which is known as a strong oxidant and is helpful for the cleavage of carbon-carbon double bonds.[84] RuO_4 can be generated upon treatment of $RuCl_3$ with an oxidant such as $NaIO_4$. The reaction initially produces sodium diperiodo-dihydroxo-ruthenate(VI), which decomposes into the tetroxide in an acid solution.



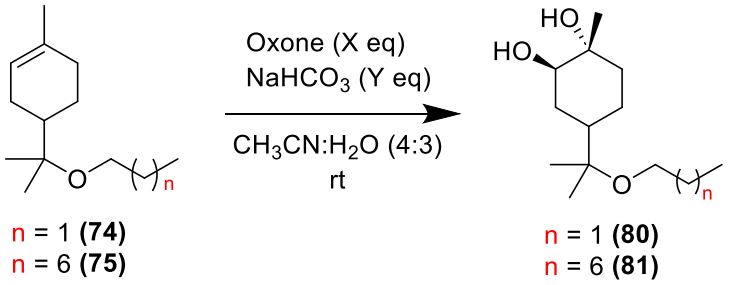
(75) **(79)** 39%

Scheme 2.12: Ruthenium-Catalysed oxidative cleavage of the alkene of a-terpenyl derivative into aldehyde-ketone

The cyclic alkene of (**75**) was subjected to ruthenium oxidation at ambient temperature for 48 hours using DCM:water as a solvent mixture (Scheme 2:12). However, the yield of this keto-aldehyde was relatively low (39%), so another synthetic route was investigated.

2.2.3.1.2 Oxone oxidative cleavage of Olefins into aldehyde-ketone in two steps

The oxone oxidative cleavage protocol of alkenes follows a number of sequential reaction steps. First, oxone epoxides the alkene of the α-terpenyl derivatives. Then, the acidic nature of the oxidant, in combination with water, induces the hydrolysis of the resulting epoxide to give the diol (Scheme 2.13).



n = 1 **(74)**
n = 6 **(75)**

n = 1 **(80)**
n = 6 **(81)**

Scheme 2.13: Dihydroxylation of a-terpenyl derivatives to afford diols

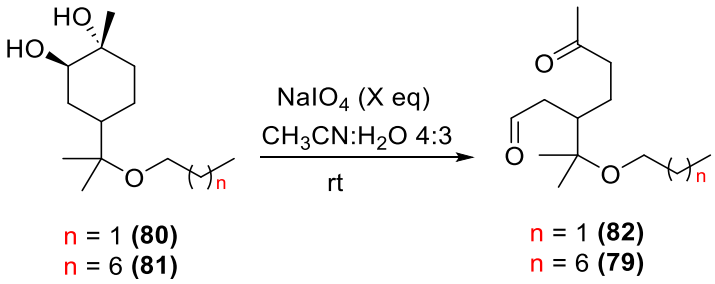
Table 2.6: The results of Dihydroxylation of a-terpenyl derivatives to afford diols

Entry	n	X (eq.)	Y (eq.)	Time (h)	Yield (%)
1	1	3	2.5	72	87
2	6	3.2	2.5	120	84

The dihydroxylation reaction was conducted at ambient temperature using an acetonitrile:water combination. It gave a good yield of around 85% for the short and long chains of the α-terpenyl alcohol derivatives (Table 2.6).[83]

Subsequently, the resulting diol was cleaved oxidatively using sodium periodate to afford the aldehyde-ketone groups. In the initial stage of diol cleavage by $NaIO_4$, the alcohol groups directly bond with iodine. This happens via two consecutive attacks from the lone pairs of each hydroxyl group, which is then accompanied by a proton transfer. In the subsequent step, the cyclic iodate ester decomposes, resulting in the formation of a ketone and an aldehyde.

It was noticed that the ratio of water to acetonitrile is critical for the reaction. When acetonitrile was used alone without water, the reaction did not proceed to have only the starting material after 72 hours (Table 2.7, entry 1). However, the ratio 4:3 acetonitrile:water yielded over 80% of the desired products.



Scheme 2.14: Oxidative cleavage of diols into ketone-aldehyde.

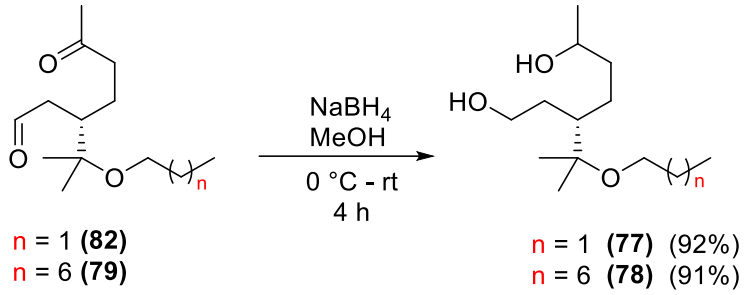
Table 2.7: The results of Oxidative cleavage of diols into ketone-aldehyde.

Entry	n	X (eq.)	$CH_3CN:H_2O$	Time (h)	Yield (%)
1	6	2	4:0	72	-
2	1	1.5	4:3	72	84
3	6	2	4:3	96	81

Now, after exploring two synthetic methods of oxidative cleavage of the alkene to aldehyde-ketone groups, we decided to explore the convertion into diols by a reduction reaction.

2.2.3.1.3 Aldehyde-ketone to diols

Sodium borohydride ($NaBH_4$) is a convenient source of hydride ions (H^-) for reducing aldehydes and ketones to primary and secondary alcohols.



Scheme 2.15: Reduction of the aldehyde-ketone to a diol.

The reaction of the keto-aldehyde reduction was carried out in methanol as a solvent for 4 hours to yield over 90% of the desired products for the short and long chains derivatives (n=1 and 6) (Scheme 2.15).

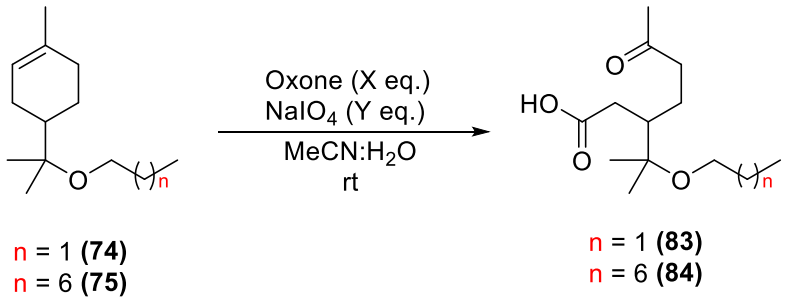
These resulting alcohols are novel compounds that can be used as monomers in condensation polymerisation. Polymerising these new diol monomers with dicarboxylic monomers will potentially afford novel polyesters.

2.2.3.2 Toward hydroxycarboxylic acids derivatives:

The oxidative cleavage of the internal double bond of terpenes into carbonyl compounds were reported by Spannring *et al*.[85] They developed a metal-free protocol that can oxidatively cleave unsaturated terpenes into carboxylic acids in a synthetically straightforward, one-pot protocol. Near stoichiometric amounts of oxone and periodate are used in aqueous acetonitrile without additional additives, acids or emulsifiers. The solvent system and the reaction temperature

profoundly influence the reactivity of the substrates; conditions have been optimised for a broad scope of alkenes.[85]

The oxidative cleavage of α-terpenyl derivatives using this product gave the desired carboxylic acids derivatives (Scheme 2.16). Different amounts of a combination of Oxone and periodate were used in aqueous acetonitrile without additional additives, acids or emulsifiers to give yields around 35%. During the optimisation, we found that the ratio of the solvent mixture MeCN: H_2O play an important role in the reaction (Table 2.8). The solubility of the product is less in this mixture MeCN: H_2O when the alkoxy chains are longer. When the reaction was left for 7 days, the yield increased by more than 75%, facilitating purification without column chromatography.

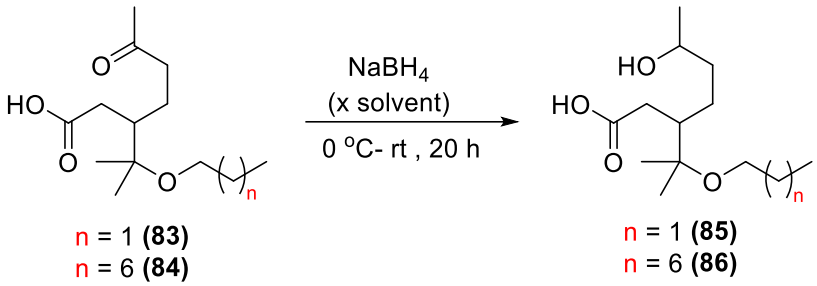


Scheme 2.16: The oxidative cleavage of α-terpenyl derivatives propyl, pentyl and octyl.

Table 2.8: The results of the oxidative cleavage of α-terpenyl derivatives propyl, pentyl and octyl.

Entry	n	Oxone (X eq.)	$NaIO_4$ (Y eq.)	MeCN: H_2O	Time (h)	Yield (%)
1	1	2	1.5	1:3	24	34
2	1	2	1.5	1:3	48	35
3	1	2	1.5	1:1	24	-
4	1	4	3	1:1	96	76
8	6	2	1.5	1:3	24	-
9	6	4	2.5	1:3	72	-
10	6	8	6	1:3	72	-
11	6	4	3	1:1	48	33
12	6	8	6.5	1:1	216	74

The next stage was to reduce the ketone into alcohol. Sodium borohydride ($NaBH_4$) was used as a selective reduction reagent under different conditions (time and temperature) to give the desired product (Scheme 2.17 and Table 2.9).



Scheme 2.17: Selective reduction of the ketone to secondary alcohol.

Table 2.9: The results of the selective reduction of the ketone to secondary alcohol.

Entry	Solvent	Yield
1	MeOH	-
2	EtOH	-
3	$NaHCO_3/H_2O$, EtOH	-
4	DCM	n=1 (96%), n=6 (91%)

The reduction reaction was carried out using different solvents. When methanol, ethanol, and a $NaHCO_3/H_2O$/EtOH mixture were used,[86] the reduction was not selective, so the carboxyl group was also reduced to alcohol. Hence, these solvents did not produce the desired product. However, using DCM resulted in a clear and high yield.

2.3 Monomers from β-pinene

One of the main components of turpentine is β-pinene, ranging between 10 and 40% depending on its source.[77] β-Pinene is a bicyclic compound with a double bond, contributing to its reactivity and characteristic pine-like aroma. Although β-pinene occurs less frequently than α-

pinene their exocyclic double bond is located more favourably for further synthesis. Therefore, novel monomers with different functional groups can be prepared from this biomass material.

2.3.1 Epoxidation of β-pinene

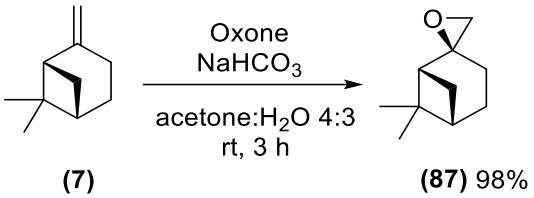
As β-pinene is one of the main compounds of turpentine oil, its epoxidation is of academic and industrial interest. Also, because of the easy functionalisation of terpene epoxides to high-added-value products, epoxidation is one of the main terpene reactions.[77] Examples of products obtained from epoxides are myrtenol, pinocarveol, pinocarvone, myrtenal, perillyl alcohol, and verbenone. Terpene epoxides, such as β-pinene epoxide, have a wide range of applications such as pharmaceutical agents, fragrance/favour ingredients, and toothpaste components. Traditionally, epoxides are produced by the epoxidation of alkenes with stoichiometric amounts of peracids (e.g., peracetic acid) as oxidants, which are hazardous and environmentally undesirable. In the last decades, the epoxidation of alkenes with H_2O_2, molecular oxygen or air has been widely reported due to its lower environmental impact and higher economic viability.[87]

Here, the epoxidation of β-pinene to 2,10-epoxypinane was carried out using potassium peroxomonosulfate (Oxone) as an oxidant and acetone as a catalyst.

Warning: The reaction between Oxone and acetone can produce dimethyldioxirane (DMDO), which is a highly reactive and potentially explosive compound. DMDO is known for its extreme instability, particularly when concentrated or exposed to heat, friction, or shock.

The procedure consists simply of stirring the substrate, $NaHCO_3$ and acetone at room temperature for 3 hours, with the dropwise addition of an aqueous solution of Oxone. The method gave the desired epoxide with a high yield of 98% (Scheme 2.18). Oxone is more environmentally friendly than *m*-CPBA, and can also be used on larger-scale reactions. Sodium

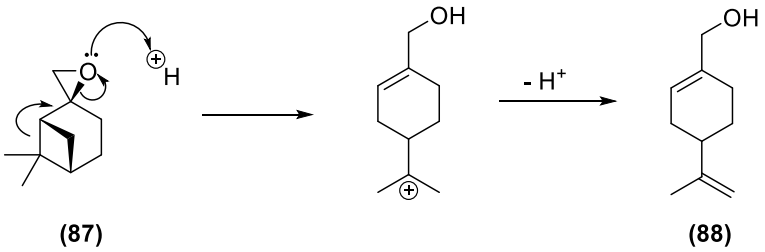
bicarbonate was used to quench excess peroxide that was found in the reaction. The structure of β-pinene epoxide was characterised by IR, LC-MS and ^{1}H NMR spectra.



Scheme 2.18: Epoxidation of β-pinene.

2.3.2 Alcohol or Amine addition

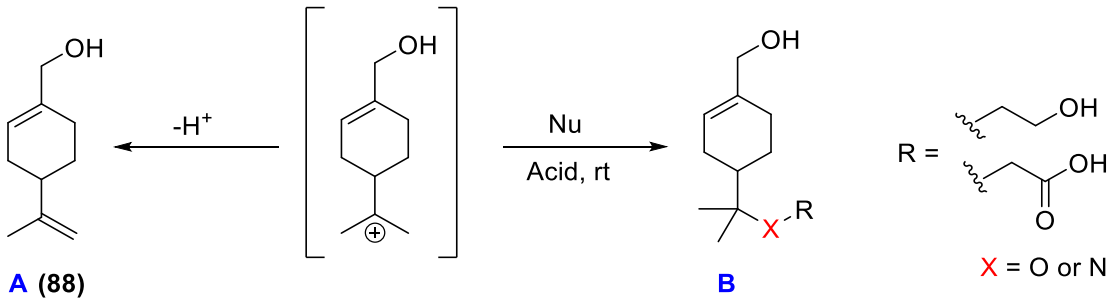
The next stage was to generate hydroxy-carboxy derivatives of this β-pinene epoxide in one reaction. Different nucleophiles such as glycolic acid, ethylene glycol and ethanol amine were used. The reaction was catalysed by different acids such as camphor sulfonic acid (CSA), p-toluenesulfonic acid (PTSA), methanesulfonic acid (MSOH), and sulfuric acid (H_2SO_4). The acid was needed to protonate the epoxide and cause the rearrangement of β-pinene to form the carbocation (Scheme 2.19). The intermediate could then be transformed with the addition of the nucleophiles.



Scheme 2.19: The arrangement of β-pinene epoxide in the presence of an acid.

None of the reactions was successful in any of the attempts to trap the cationic intermediate, regardless of the power of the nucleophile or the acids (Scheme 2.20 and Table 2.10), to afford the desired product. It was thought the amine group of ethanol amine would be a stronger

nucleophile, compared to the hydroxy groups in ethylene glycol and glycolic acid, which could make this reaction go to completion. However, it is likely that the amine was protonated under these conditions and did not behave as a nucleophile, so the product was always **(88)**, and the yield varied between 29% and 65% (Scheme 2.20).



Scheme 2.20: Attempts of nucleophilic addition on β-pinene epoxide to afford hydroxy -acids monomers

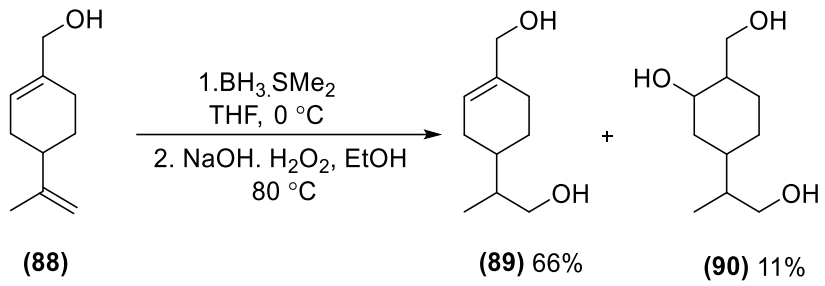
The resulting product has a new terminal alkene group that can be used in radical polymerisation. The two alkene groups can also be functionalised to afford novel monomers suitable for polycondensation.

Table 2.10: Attempts of nucleophilic addition on β-pinene epoxide to afford hydroxy -acids monomers.

Entry	R group	Acid catalysis	Quantity of acid	Solvent	Time (h)	Yield (%) A	Yield (%) B
1	$HOCH_2COOH$	CSA	0.0026 eq	*t*BuOH	16	32	0
2		PTSA	0.0016 eq	*t*BuOH	2	31	0
3	$HOCH_2CH_2OH$	$MeSO_3H$	1 eq	toluene	3	37	0
4		$MeSO_3H$	1 eq	hexane	3	35	0
5		H_2SO_4	1 drop	hexane	3	40	0
6		CSA	0.0026 eq	-	24	65	0
7		PTSA	0.0016 eq	-	6	36	0
8	$H_2NCH_2CH_2OH$	H_2SO_4	1 drop	-	3	29	0
9		CSA	0.0026 eq	-	16	33	0
10		PTSA	0.0016 eq	-	3	32	0

2.3.3 Towards diols

The two alkene groups can also be functionalised to afford novel monomers suitable for polycondensation. Hydroboration is an addition reaction between an alkene and a borane. A C-C pi bond is broken in hydroboration, and a C-H bond and a C-B bond are formed. Hydroboration is stereoselective for syn addition – that is, meaning that hydrogen and boron are delivered to the same side of the alkene. Oxidation of the resulting organoborane with hydrogen peroxide (H_2O_2) replaces the C-B bond with a C-OH bond. Oxidation of the C-B bond occurs with complete retention of stereochemistry. The notable outcome of hydroboration-oxidation is the formation of alcohol on the least substituted carbon of the alkene ("anti-Markovnikov" regioselectivity).[88]



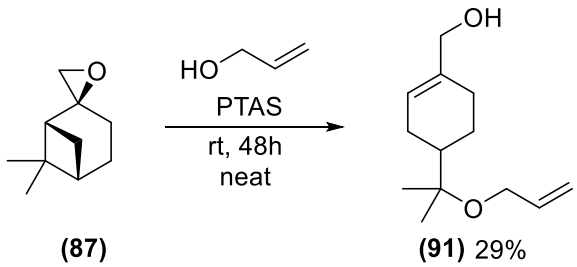
*Scheme 2.21: Hydroxylation of the alkene groups of (**88**).*

This hydroboration of the peillyl alcohol (**88**) was carried out using dimethyl sulfide borane in tetrahydrofuran as a solvent at 0 °C. After two hours, hydrogen peroxide and sodium hydroxide were added in the presence of ethanol as a solvent at 80 °C to yield two products (**89** and **90**) suitable for polycondensation with dicarboxylic chemicals.

2.3.4 Alkene addition

β-Pinene epoxide is a suitable substrate for further functionalisation, utilising the epoxide's reactivity. Although the di-alcohol addition to β-pinene epoxide did not yield the desired

product in scheme 2.20, adding allyl alcohol to β-pinene epoxide resulted in the desired addition of the alkene group. The reaction was carried out using p-toluenesulfonic acid (PTSA) as a catalyst at ambient temperature for 48 h to yield 29 % of the alyl ether product (Scheme 2.22).

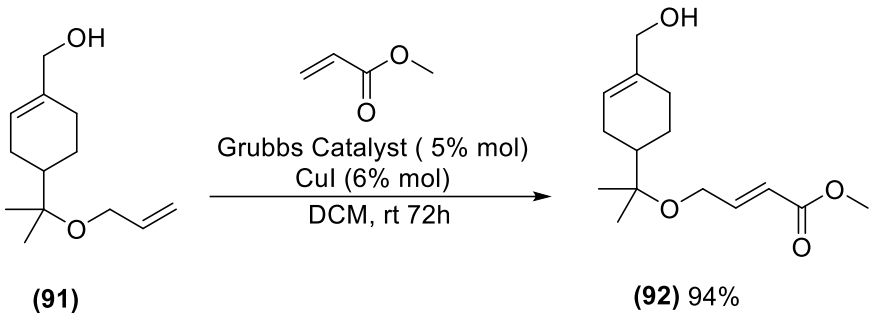


Scheme 2.22: Adding allyl alcohol to β-pinene epoxide.

This novel monomer can potentially be polymerised using allyl radical polymerisation to form a polymer with a cyclo-functionalisable side group and a hydroxy group.[89] It can also be used with other olefin substrates to produce either novel monomers or polymers by a metathesis reaction.[90-92]

2.3.5 Acrylate addition

(**91**) is a suitable substrate for olefin cross-metathesis. Olefin metathesis has been widely explored for chemical diversification. Cross metathesis (CM) with acrylic acid derivatives is an example of importance. High-profile targets accessed via acrylate metathesis range from high-value antioxidants to natural products of medicinal relevance. Cross-metathesis (CM) of acrylates with biomass chemicals is likewise key to transforming unsaturated fats and oils into renewable platform chemicals, including novel building blocks for high-performance surfactants.[93-95]



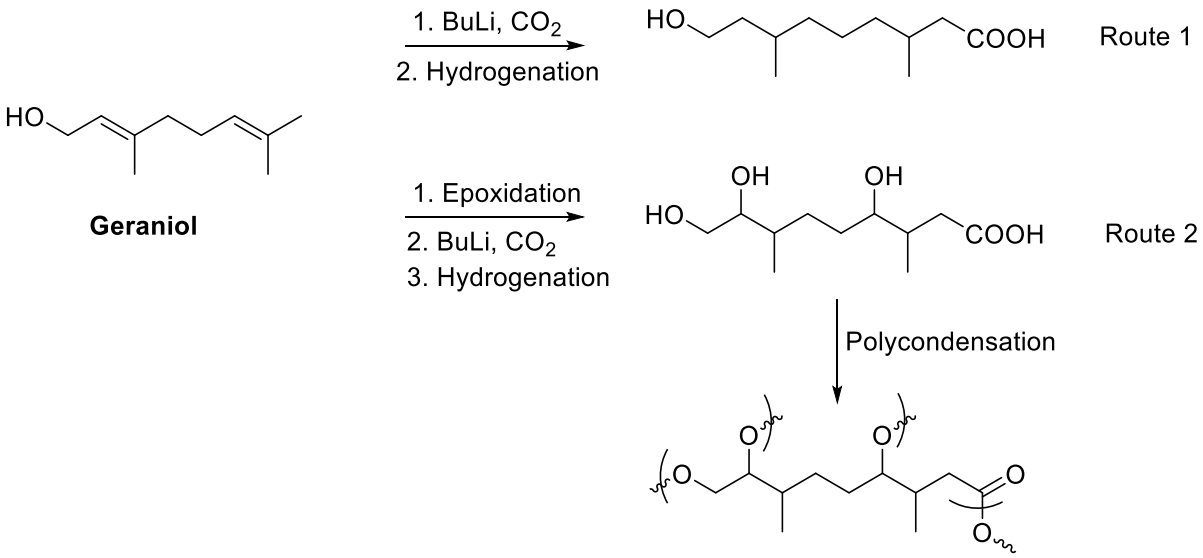
(91) **(92)** 94%

Scheme 2.23: Acrylate addition by a cross-metathesis reaction using Grubbs catalyst

Alcohol (**91**) was subjected to cross-metathesis with methyl acrylate using Grubbs' second-generation catalyst in the presence of a catalytic amount of CuI additive (Lipshutz's strategy) in dichloromethane as a solvent at ambient temperature for 72 h to yield 75 % of (**92**) product. The product can be hydrolysed to generate the carboxylic acid derivative and methanol. The potential hydroxy-carboxy acid product could be utilised in polycondensation for novel polyesters. This polyester will have two alkene groups; cyclic and aliphatic, which can be utilised for post-polymerisation modifications.

2.4 Monomers from Geraniol:

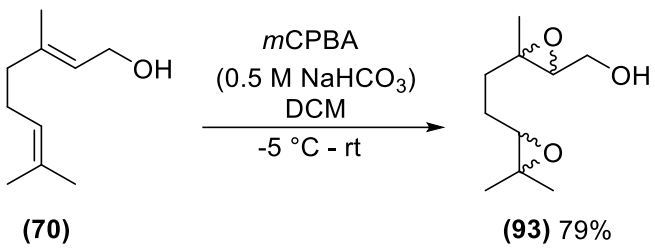
Geraniol is a commercially important terpene alcohol found in the essential oils of several aromatic plants. It is one of the most critical molecules in the flavour and fragrance industries.[59] Because geraniol has two alkene groups in its structure, several chemical modifications can be applied to it. One of these is epoxidation. Geraniol could be converted into either lipophilic or hydrophobic hydroxy acid monomers by using lithiation/carboxylation techniques either before (Route 1) (Scheme 2.24) or after epoxidation (Route 2). The potential product of Route 2 could be polymerised to a polyester via polycondensation.



Scheme 2.24: Converting geraniol into lipophilic and hydrophilic hydroxy acids to be used as monomers to make polyesters via polycondensation

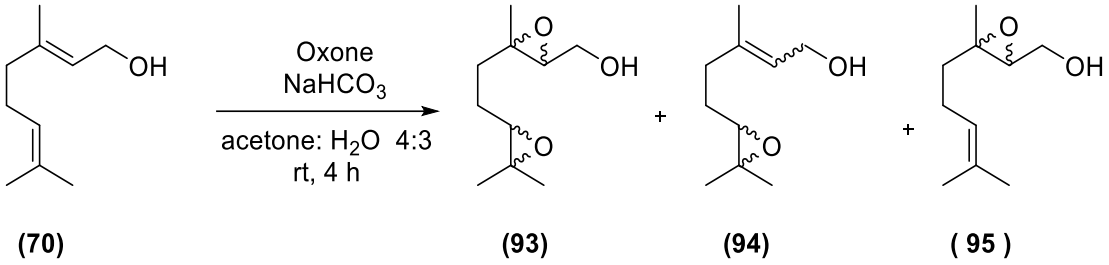
2.4.1 Epoxidation

Theoretically, both double bonds in geraniol can react with epoxidation reagents. Thus, three epoxide products can form (two epoxides, one epoxide of the allyl alcohol or one epoxide of the other alkene). A standard epoxidation procedure that uses *meta*-chloroperoxybenzoic acid (*m*CPBA) converted the two alkenes into epoxides (Scheme 2.25). The reaction was carried out at a relatively lower temperature (-5 °C to ambient temperature) than what had been reported, where it was carried out at 0 °C to ambient temperature.[96] This condition afforded **(93)** at 79% yield, which was higher than reported (61%).



Scheme 2.25: Epoxidation of geraniol into epoxides derivatives using mCPBA.

When another oxidation reagent was used, Oxone in acetone (dimethyl dioxirane made in-situ) at ambient temperature, the reaction yielded three different epoxides (Scheme 2.26) and (Table 2.11).

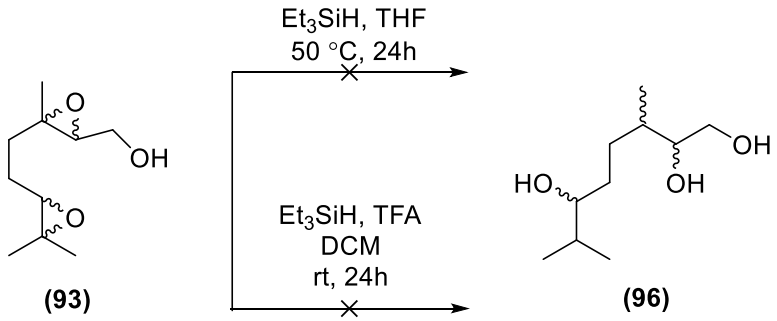


Scheme 2.26: Epoxidation of geraniol into epoxides derivatives using Oxone.

Table 2.11: Results of the epoxidation of geraniol into epoxides derivatives using Oxone.

Entry	Oxone (eq.)	$NaHCO_3$ (eq.)	Di-epoxide	Mono-epoxide	
				7,8	3,3
1	2.5	5	85%	-	-
2	1.7	2.5	18%	50%	3%
3	0.7	1.25	19%	17%	6%

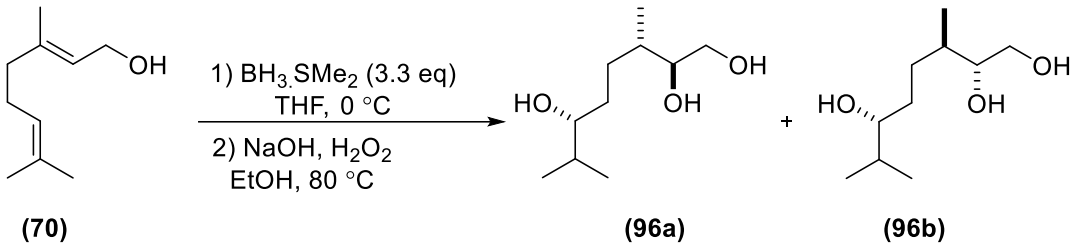
All attempted ring-opening of the bis-epoxides using triethyl silane under acidic or neutral conditions[97]were unsuccessful (Scheme 2.27). When THF was used as a solvent at 50 °C for 24 or 48 h, there was no reaction, as the TLC showed only the starting material. The starting material was polymerised when the acidic conditions were applied using TFA and DCM as a solvent at ambient temperature for 24 h.



(Scheme 2.27): Unsuccessful attempts for ring-opening of the bis-epoxied using triethyl silane under acidic or neutral conditions.

2.4.2 Hydrolysis:

Hydroboration is an addition reaction involving an alkene and a borane, where the C-C π bond is cleaved, leading to the simultaneous formation of C-H and C-B bonds. A defining characteristic of the hydroboration-oxidation process is its anti-Markovnikov regioselectivity, which results in the hydroxyl (-OH) group attaching to the least substituted carbon of the alkene. [88,98]

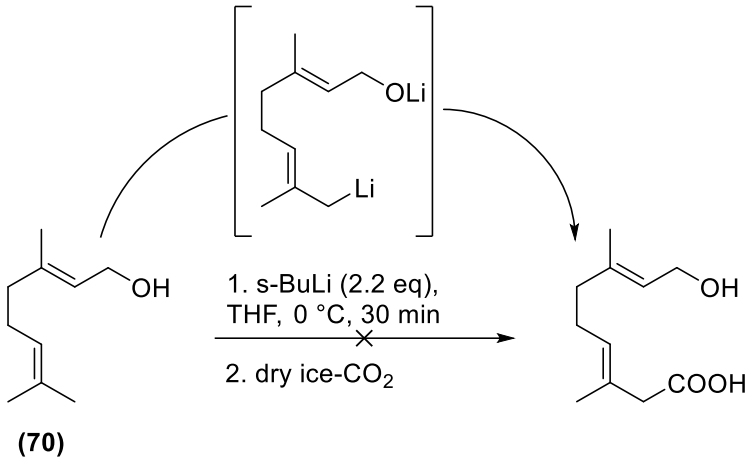


Scheme 2.28: Hydrolysis of Geraniol via hydroboration.

This hydroboration oxidation reaction was carried out using dimethyl sulfide borane in tetrahydrofuran as a solvent at 0 °C. After 5 h, hydrogen peroxide and sodium hydroxide were added in the presence of ethanol as a solvent at 80 °C to yield 62% of two diastereomeric products (**96a** and **96b**) that are suitable for polycondensation with dicarboxylic chemicals to form polyesters.

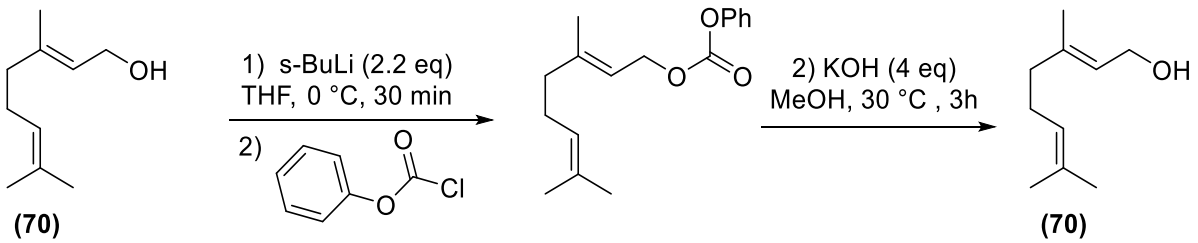
2.4.3 Towards hydroxy-carboxy derivatives:

A carboxylation reaction was attempted by double deprotonation of geraniol with s-BuLi followed by reaction with dry ice to prepare a hydroxy acid derivative from geraniol.



Scheme 2.29: Failed attempt of carboxylation using dry ice as a source of CO_2.

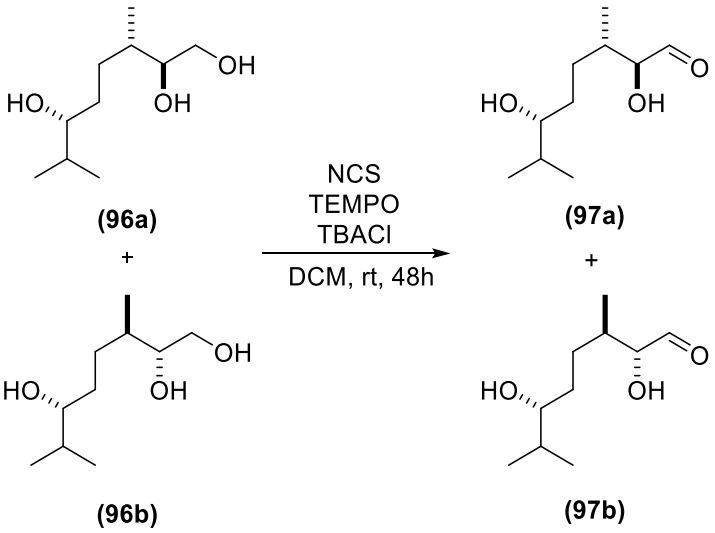
The reaction was unsuccessful, giving only the starting material (Scheme 2.29), suggesting the second deprotonation may not have proceeded.[99] We hypothesised that full deprotonation might not occur in the presence of water, which was present in the dry ice, and that water would react with butyl-lithium (s-BuLi) to give butane and LiOH. Thus, we decided to use phenyl chloroformate as a source of CO_2. When secondary butyl-lithium (s-BuLi) was used in the presence of phenyl chloroformate, the reaction did not happen on the desired site. The ^{1}H-NMR showed coupling happened on the hydroxy alpha hydrogen. Then, when the potassium hydroxide was added, we had the starting material back. Thus, s-BuLi is deprotonations the hydroxyl but likely not generating the required product. The basicity of s-BuLi can be increased by adding hexamethylphosphoramide (HMPA). However, this additive is highly toxic. Thus, we decided not to continue this investigation further.



Scheme 2.30: A scheme to show the reaction of s-BuLi in the presence of phenyl chloroformate with Geraniol.

With HMPA enabling the direct formation of a hydroxy acid from geraniol, we pursued a selective oxidation of the primary alcohol in geraniol derivatives to synthesise a hydroxy acid monomer through this approach.

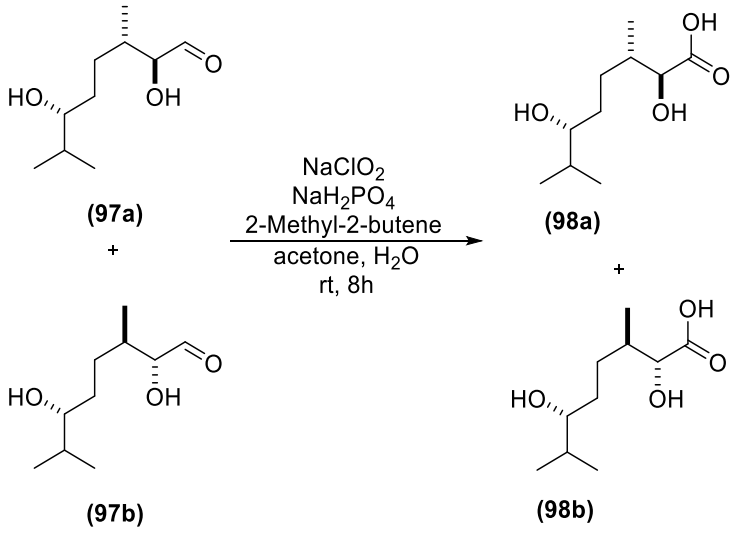
2,2,6,6-Tetramethyl-1-piperidinyloxy (TEMPO) catalyses efficient oxidation of primary alcohols to aldehydes by N-chlorosuccinimide (NCS) as a stoichiometric oxidant in a biphasic dichloromethane, in the presence of tetrabutylammonium chloride. Alcohols are readily oxidised with no overoxidation to carboxylic acids. Very high chemoselectivities are observed when primary alcohols are oxidised in the presence of secondary ones. Secondary alcohols are oxidised to ketones with a much lower efficiency.[100]



Scheme 2.31: Selective oxidation of the primary alcohols to afford the aldehyde derivatives

Now, selective oxidation of the aldehyde can be done by the Pinnick oxidation, where aldehydes can be oxidised into their corresponding carboxylic acids using sodium chlorite ($NaClO_2$) under mildly acidic conditions. The suggested reaction mechanism features chlorous acid as the primary oxidising agent, produced under acidic conditions from chlorite. First, the chlorous acid was added to the aldehyde. The resulting structure undergoes a pericyclic

fragmentation in which the aldehyde hydrogen is transferred to oxygen on the chlorine, with the chlorine group released as hypochlorous acid (HOCl). The HOCl byproduct, itself a reactive oxidising agent, can be a problem in several ways. The $NaClO_2$ reactant can be degraded, rendering it unavailable for the intended reaction. It may also lead to unwanted side reactions with organic compounds. To mitigate the effects of HOCl interference, a scavenger is typically incorporated into the reaction to neutralise the HOCl as it is produced. For instance, a sacrificial alkene-containing compound can be included in the reaction mixture. This alternative substrate reacts with the HOCl, thereby preventing it from participating in reactions that might disrupt the Pinnick reaction itself. 2-Methyl-2-butene we used in our case. The reaction was carried out in acetone and water at room temperature for eight hours to yield 60%.[101]



Scheme 2.32: Selective oxidation of the aldehyde to afford the desired carboxylic acids that can be used to make polyesters.

2.5 Conclusions:

In this chapter, several synthetic routes were explored to afford different monomers precursors and monomers with different polymerisable groups from biomass materials: α-pinene, limonene, β-pinene and geraniol.

The ethylene glycol addition to α-pinene gave a low yield, around 10% of the desired product (**71**), and a higher yield, around 35%, was obtained with 1-propanol **(72)** and 1-octanol **(73)**. The highest yield, 52% **(74)**, was obtained when Lewis acid catalysts were used. The alcohol derivative with methacrylate afforded 60% of the desired product **(76),** which can be used for radical polymerisation.

The cyclic-alkene group of α-pinene was utilised to open the ring and afford high yields of monomers with diols (**77**, **78**). Furthermore, these diols were converted into the hydroxy-carboxy derivatives (**85**, **86**). Both diols and the hydroxy-carboxy derivatives can be utilised for polycondensation and produce novel polyesters.

The addition of alcohol to β-pinene produced a monomer (**88**) with two polymerisable groups: alcohol and olefin. This monomer was further functionalised to afford novel diols (89, 90) suitable for polycondensation that produces novel polyesters. β-Pinene epoxide was also utilised for akene and methacrylate additions **(91**, **92)**.

Geraniol was used to prepare epoxides, diols, and novel hydroxy-carboxy derivatives (**93**, **94**, **95**, **96,** and **98**) suitable for polycondensation and the synthesis of novel polyesters.

Chapter Three:

3. Monomer Derivatives from Furfural

3.1 Introduction:

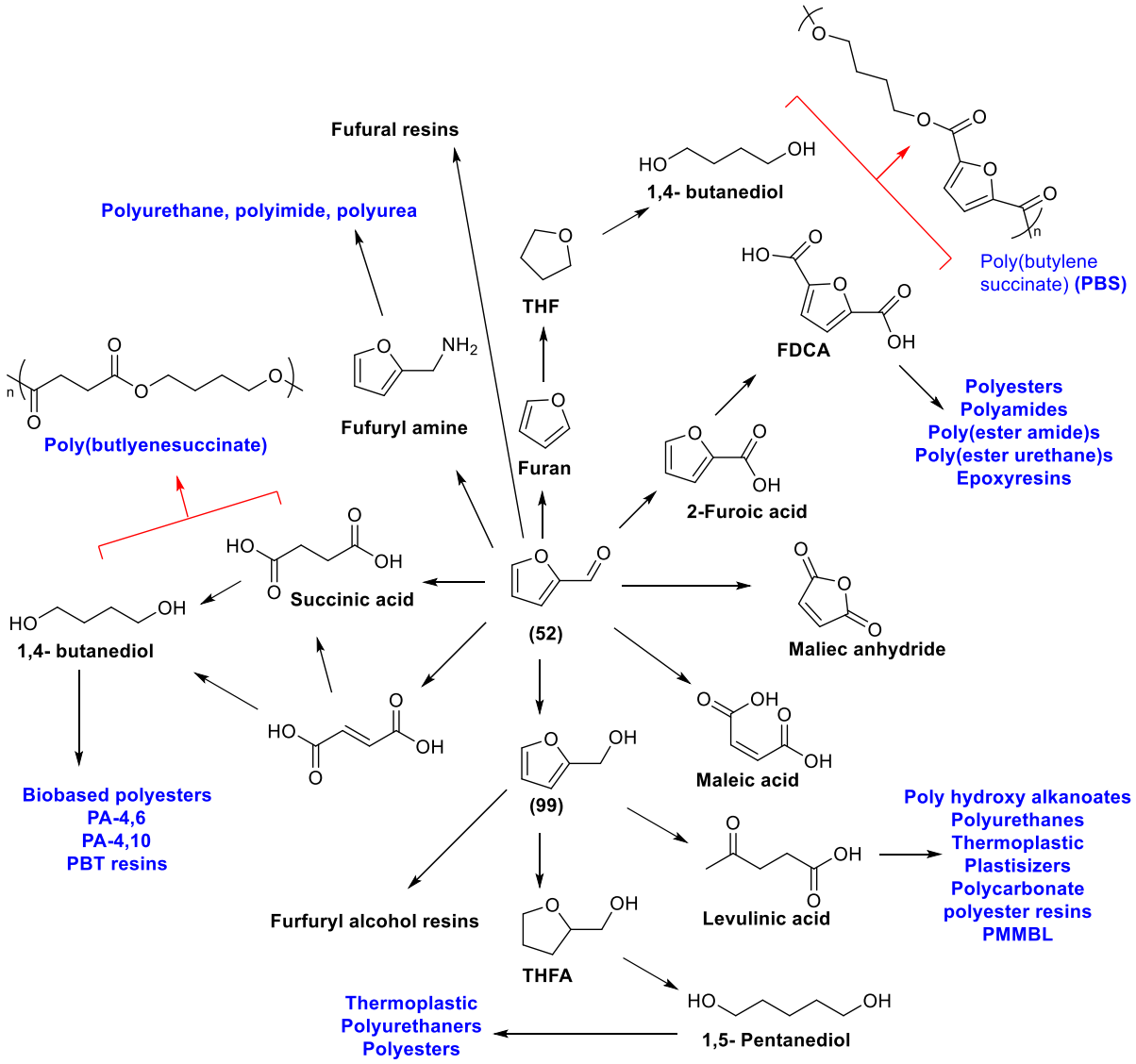
Furfural (**52**) is a naturally occurring dehydrated derivative of xylose, which is a pentose sugar commonly present in significant amounts within the hemicellulose component of lignocellulosic biomass.[102] It is produced on an industrial scale (400–500 kt a year).[102] This material deserves consideration as a potential feedstock of biobased polymers because it can be converted into various derivatives that are components of biobased polymers, as presented in Scheme 3.1. The aldehyde functional group in furfural allows for a variety of reactions to take place, including acylation, acetylation, reductive amination to amines, reduction to alcohols, oxidation to carboxylic acids, Grignard reactions, and aldol and Knoevenagel condensation.[102] Furfural is, therefore, a versatile platform chemical that can be used as a raw material to create additional high-value goods such as inks, plastics, antacids, adhesives, nematicides, fungicides, fertilisers, and flavouring compounds.[103] The most common furfural derivatives that are potential polymer components are:

1- **1,4-Butanediol** is used to manufacture various polymers, such as poly(butylene succinate) (PBS), poly(butylene terephthalate) (PBT), and poly(butylene furanoate) (PBF).[104]

2- **2,5-Furandicarboxylic acid** can replace the petro-derived terephthalic acid used to synthesise polyesters.[104]

3- **Furfurylamine** is an important chemical intermediate in the preparation of polyurethanes and epoxy resins.[104]

4- **Levulinic acid** was chosen as one of the top 12 promising building block chemicals by the US Department of Energy (DOE) and has wide applications in the manufacturing of plasticisers and solvents.[104]

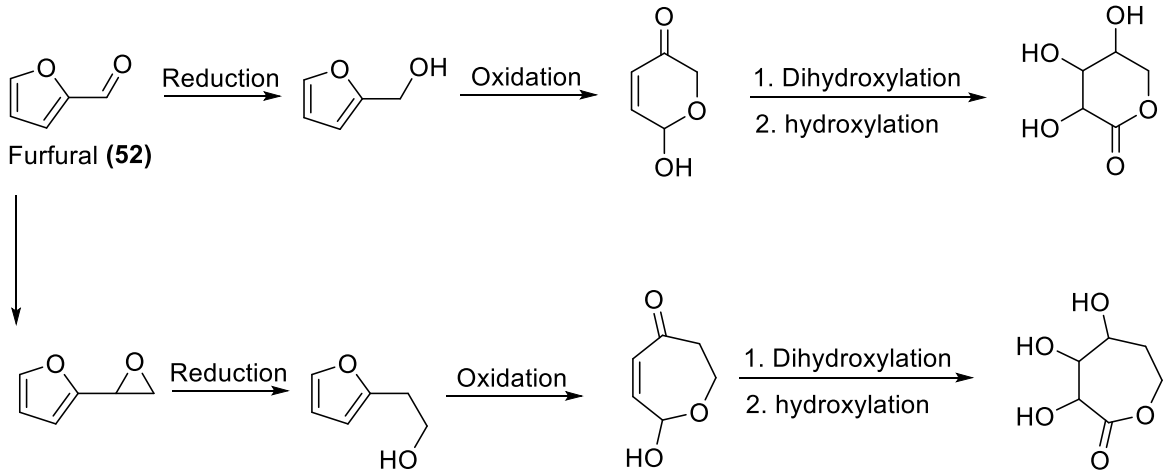


Scheme 3.1: Furfural as a synthetic platform for bio-based polymers.[104]

5- **Maleic acid and maleic anhydride** are important raw chemicals used in the production of alkyl and polyester resins, surface coatings, lubricant additives, copolymers, and plasticisers.[104]

3.2 Aim and Objectives:

Furfural serves as a key precursor for the successful synthesis, characterisation, and polymerisation of various monomers. [46-51] Beyond its role in furan-based derivatives, furfural can also be transformed into non-furan monomers, such as hydroxy acids or cyclic counterparts. In this study, furfural will be utilised to synthesise novel 6- or 7-membered ring lactones, which can undergo ring-opening polymerisation to produce hydrophilic polyesters (Scheme 3.2). The hydroxyl groups of these rings could be protected before carrying out living ROP, and then they can be deprotected post-polymerisation.



Scheme 3.2: Converting furfural into novel 6 or 7-member ring lactones where they can be polymerised via ring-opening polymerisation to make hydrophilic polyesters.

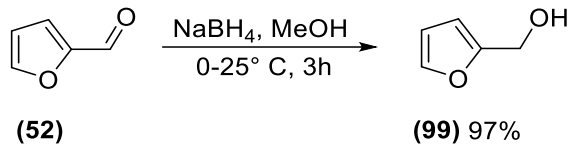
3.3 Results:

3.3.1 Furfural Reduction:

In 2014, it was reported that approximately 62% of furfural was globally converted into 2-furfuryl alcohol (FA) (**99**), which is primarily used in the production of foundry resins.[105]

Resins made from FA alone, as well as those formed through copolymerisation with other chemicals such as formaldehyde, phenolic compounds, and urea, exhibited notable chemical, thermal, and mechanical properties.[106] Other applications include its use as a precursor for fibre-reinforced plastics and pharmaceuticals, a reactive solvent for phenolic resins, and an adhesive and wetting agent.[107]

Furfural is converted to FA **(99)** by the selective hydrogenation of the C=O bond. Royer *et, al,* published a review in 2018 about the production of FA **(99)** from furfural using several metal catalytic methods.[108] Here, furfural was selectively reduced to FA **(99)** with sodium borohydride in methanol at 0 °C to yield 97%.[109] This proceeds *via* a two-step mechanism consisting of nucleophilic addition followed by protonation. The reaction was monitored by thin-layer chromatography (TLC), and once the reaction was completed, the product was extracted by ethyl acetate.



(52) **(99)** 97%

*Scheme 3.3: Furfural to furan-2-ylmethanol **(99)**.*

The next stage was to use ring opening and subsequent ring closure reaction on the product **(99)**. The Achmatowicz reaction can convert furfuryl alcohols into dihydropyranone acetals (also identified as pyranuloses), by oxidative ring expansion/ rearrangement to smoothly provide 6-hydroxy-2*H*-pyran-2(3*H*)-ones.

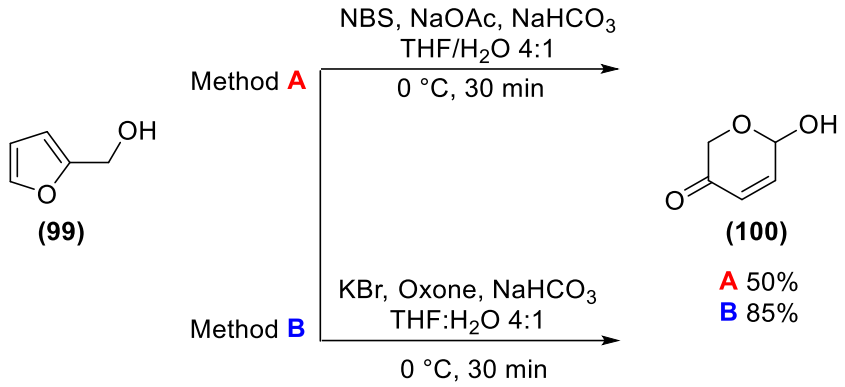
3.3.2 Oxidation towards 6-membered Ring:

The Achmatowicz rearrangement (AchR) is an oxidative ring-expansion rearrangement of functionalised furfuryl alcohols to densely functionalised dihydropyranone acetals. It is a

powerful and versatile synthetic tool for the preparation of tetrahydropyrans, dihydropyranones, oxidopyrylium, δ-lactones, and pyranoses, etc.[110] AchR could be performed with various oxidation methods, including Br_2/MeOH, N-bromosuccinimide (NBS), in situ generated dimethyl dioxirane (DMDO), *m*-chloroperoxybenzoic acid (*m*-CPBA), magnesium mono-peroxypthalate, metal−base oxidant, titanium(IV) silicalite/H_2O_2, phenyliodine(III) diacetate (PIDA), photolytic oxidation (O_2/hν), electrochemical oxidation, and enzymatic transformations.[110] Among these methods, NBS and *m*-CPBA are the most widely used oxidants for their simple operation in practice, tolerance of many functional groups, and reliably high yield in most cases.[110] However, the major drawback of these two protocols is the generation of stoichiometric organic side product (*m*-chlorobenzoic acid or succinimide), which usually requires purification by column chromatography.[110]

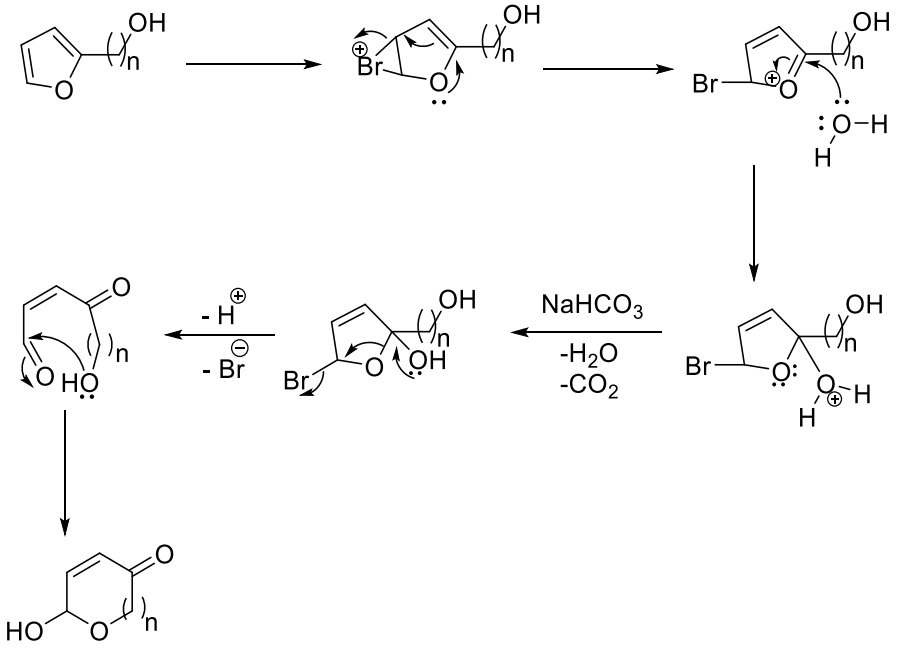
n this research, the ring expansion of 2-furfuryl alcohol (**99**) into (**100**)—involving ring opening followed by ring closure—was investigated using two methods using an Achmatowicz rearrangement (Scheme 3.4).

Initially, *N*-bromosuccinimide (NBS) was used as an oxidant with a solvent mixture THF/H_2O (method A – Scheme 3.4), and the obtained yield was 50%. Secondly, the protocol of Guodong Zhaoa and Rongbiao Tong was explored using (KBr/oxone) in the presence of chromatographic alumina (Al_2O_3) 5 mol%. KBr is used as the catalyst and oxone as the stoichiometric terminal oxidant.[110] In our hands, the yield of **100** was relatively low 25%. In an attempt to obtain a better yield, we deviated from the protocol by using a solvent mixture THF/H_2O (4/1), and the yield was more than 85% with K_2SO_4 as the only side product, which significantly facilitates the purification (method B in Scheme 3.4).[110,111]



*Scheme 3.4: Two methods (A and B) for ring opening and subsequent ring closure of 2-furfuryl alcohol **(99)** into **(100)** by Achmatowicz rearrangement.*

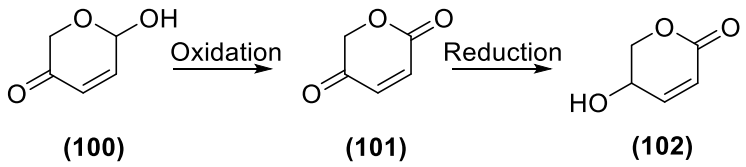
We found that the solvent mixture was critical to improve the yield, so THF/H_2O (4/1) solution probably helped solubilise the reagents of both organic substrates (furfuryl alcohols) and inorganic reagents. The mechanism of the latter method depends on the oxidation of the bromide (KBr) with oxone to generate an active transient brominating agent ([Br^+] such as HOBr or Br_2).



Scheme 3.5: Achmatowicz rearrangement with a possible mechanism.[110]

The expansion (ring opening and subsequent ring closure) would produce the dihydropyranone acetal with a generation of K_2SO_4 (potassium used as the alkali counterion) as the only side

product and release of the catalytic bromide, which would be oxidised again by Oxone for the subsequent catalytic cycles (Scheme 3.5). After obtaining the six-membered ring by the Achmatowicz reaction, this allylic alcohol can be converted into lactone as a monomer suitable for polymerisation by ring-opening polymerisation. Initially, the attempts to obtain **(102)** were planned to be in two steps: first, oxidising the alcohol of **100** to afford the lactone **(101)**, then reducing the carbonyl of the allyl ketone into allylic alcohol **(102)** (Scheme 3.6).



*Scheme 3.6: Oxidation of **(100)** to afford lactone then reduce the reducing carbonyl of the allyl ketone into allylic alcohol **(102)**.*

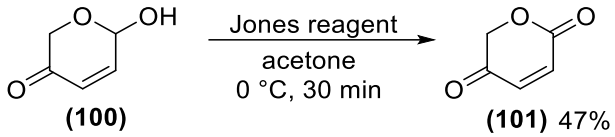
A less strong alternative to chromic acid is pyridinium chlorochromate (PCC). From primary alcohols to aldehydes and from secondary alcohols to ketones, PCC oxidises alcohols one step up the oxidation ladder. PCC will not oxidise aldehydes to carboxylic acids, in contrast to chromic acid. The reaction was conducted in dichloromethane (DCM) for 3 hours at 0 ° - 5° C but no change to the starting material was observed as the reaction was monitored by thin-layer chromatography (TLC).

*Table 3.1: The results of the reactions to convert **100** into **101** using different catalysts and conditions.*

Entry	Catalyst	Eq.	Solvent	Time (h)	Yield (%)
1	Pyridinium chlorochromate (PCC)	1.15	DCM	3	0
2	Aluminum isopropoxide $Al(O^iPr)_3$	1.8	^{i}PrOH	3	0
3	Manganese dioxide (MnO_2)	4	DCM	6	0
4	Manganese dioxide (MnO_2)	8	DCM	72	0
5	Jones Reagent	-	Acetone	45 min	47

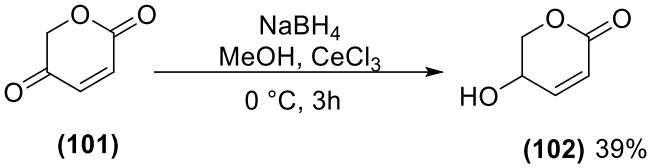
The second attempt was made using aluminium isopropoxide ($Al(i\text{-}PrO)_3$). $Al(i\text{-}PrO)_3$ is also used to oxidise alcohols to yield aldehydes and ketones and is known as the Oppenauer oxidation.[112] The alcohol substrate binds to aluminium, and the ketone coordinates with it, forming a six-membered transition state that allows the alkoxide to transfer a hydride to the ketone, yielding a ketone and an *i*-propyl alcohol, respectively. However, the reaction is reversible, favouring a large excess of the starting ketone. Also, when ($Al(i\text{-}PrO)_3$) was used for 6 hours no change to the starting material was observed as the reaction was monitored by TLC. I think the reason why no reaction was made using these two reagents is because these reagents are not suitable for oxidising primary or secondary allylic alcohols. Therefore, manganese dioxide (MnO_2) was also used as a common mild oxidising agent that selectively oxidises primary or secondary allylic and benzylic alcohols.[112] In this reaction, the hydroxyl anion binds coordinatively to hydrated $MnO(OH)_2$ on the catalyst's surface. Then breaking of a C–H bond and hydrogen transfer to manganese oxide form an allyl-radical. An electron transfer leads to the desired aldehyde or ketone. This agent was used with **(100)** up to 72 hours, but no oxidation reaction was made as only starting material was observed by TLC. The reaction is reversable, and the mechanism forms an allyl-radical that needs to be stabilised, so if the allyl-radical of **(100)** was not stabilised then the oxidation will not proceed.

Investigating the literature, we found a similar substrate (with a different functional group) which used Jones reagent to give the desired oxidation with 84% yield.[113] Hence, Jones reagent was used on **(100)**. The Jones reagent is a mixture of chromic anhydride and diluted sulfuric acid ($CrO_3 + H_2SO_4 + H_2O$) in acetone to form dichromic acid ($H_2Cr_2O_7$) and chromic acid (H_2CrO_4). It is used in the oxidation of secondary alcohols that do not contain acid-sensitive groups to corresponding ketones. This novel reaction successfully yielded 47% of the desired product (Scheme 3.7). This was confirmed by ^{1}H and ^{13}C NMR.



*Scheme 3.7: Oxidation of **(100)** to afford lactone **(101)** using Jones reagent.*

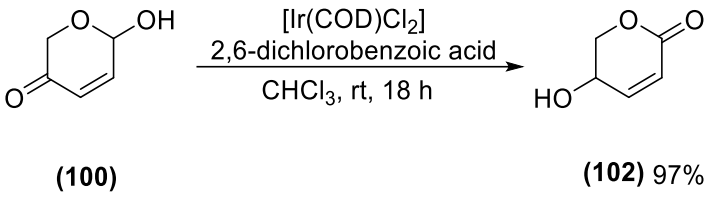
Initially, the allyl ketone **(101)** purification by silica column was attempted, but the product decomposed due to instability. Therefore, a crude sample of **100** was reduced into allylic alcohol **(102)** using Luche reduction method (Scheme 3.8). Luche reduction is the selective organic reduction of α, β-unsaturated ketones to allylic alcohols with sodium borohydride and lanthanide chlorides, mainly cerium (III) chloride, in methanol or ethanol. This novel reaction yielded 39% when the reaction was carried out at 0 °C for 3 hours. This reaction was reported on a similar substrate to yield around 96% when the reaction was carried out at -78 to 0 °C for 110 minutes.[114] Hence, this reaction could be repeated at a lower temperature to afford a better yield potentially.



*Scheme 3.8: Reduction of **(101)** to afford 5-hydroxy-5,6-dihydro-2H-pyran-2-one **(102)**.*

To avoid this low yield and in order to obtain the desired lactone in one step, another synthetic method was applied using cyclooctadiene iridium chloride dimer which is an organoiridium compound where COD is the diene 1,5-cyclooctadiene (C_8H_{12}) (Scheme 3.9). To the best of our knowledge, this reaction oxidation was reported once recently by Dangalov *et al.*[115] However, the reaction yielded only 26% of the desired product when carried out in chloroform at 20 °C. Our approach utilised different reaction conditions, resulting in a highly stereoselective synthesis of lactones (**102**) from the epimeric mixtures of Achmatowicz

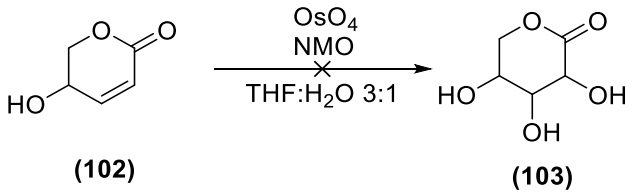
rearrangement products (**100**). This transformation occurred through an internal redox isomerisation process, yielding the desired product in a single step with an excellent yield (97%).[116]



*Scheme 3.9: Oxidation and reduction of **100** to afford 5-hydroxy-5,6-dihydro-2H-pyran-2-one **102** in one step.*

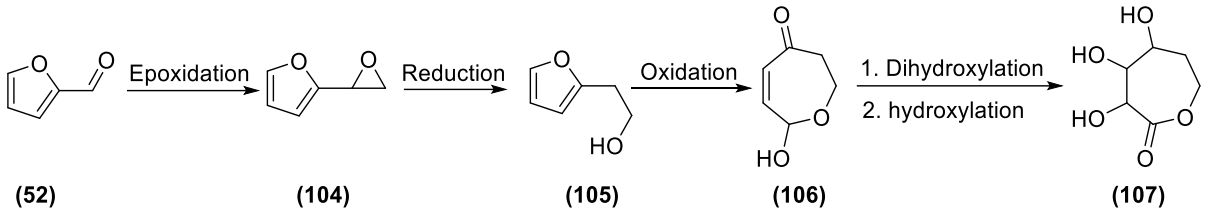
3.3.3 Dihydroxylation:

The next step was to di-hydroxylate **(102)** using osmium tetroxide (Scheme 3.10). The mechanism involves a concerted *cis* addition to form a cyclic osmate ester, which then hydrolyses to form the diol. The Upjohn dihydroxylation allows the *syn*-selective preparation of 1,2-diols from alkenes by the use of osmium tetroxide as a catalyst and a stoichiometric amount of an oxidant such as NMO (N-methyl morpholine-N-Oxide). This reaction was not successful because of the poor electron density of the olefin because of the mesomeric effect of this α,β-unsaturated carbonyl.[117]



*Scheme 3.10: Dihydroxylation of (**102**) to afford the cis-diol derivative.*

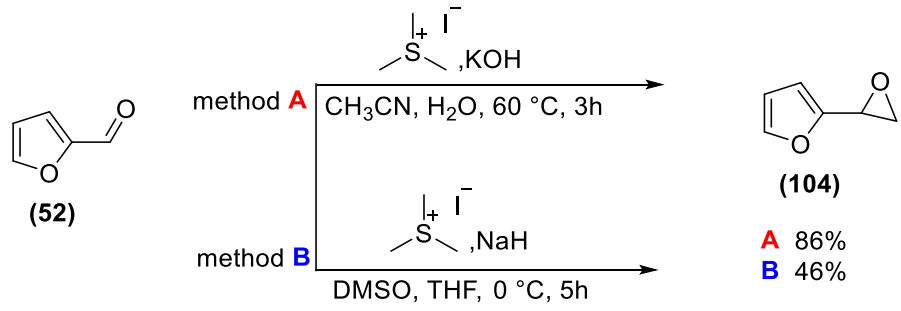
Now, another schematic pathway was explored to afford the 7-membered ring from furfuryl (Scheme 3.11).



Scheme 3.11: A proposed route to convert furfural into novel 7-member ring lactones that can be polymerised via ring-opening polymerisation to make hydrophilic polyesters.

3.3.4 Fufural Epoxidation:

Furfuryl **(52)** was epoxidised using two different methods (Scheme 3.12) using the Johnson–Corey–Chaykovsky reaction (sometimes referred to as the Corey–Chaykovsky reaction or CCR). The reaction consists of nucleophilic addition of a sulfonium ylide to the carbonyl of the aldehyde. A negative charge is transferred to the heteroatom (oxygen) and because the sulfonium cation is a good leaving group, it gets expelled, forming the ring.[118] In method A, trimethyl sulfonium iodide in the presence of potassium hydroxide gave the desired epoxide **(104)** with 86% yield. This reaction was reported by Lemini *et al.* with a comparable yield (84%).[118] In method B, the epoxidation was conducted by reacting furfuryl **(52)** with a mixture of trimethyl sulfonium iodide and sodium hydride to afford the desired product with 46% as reported.[119]

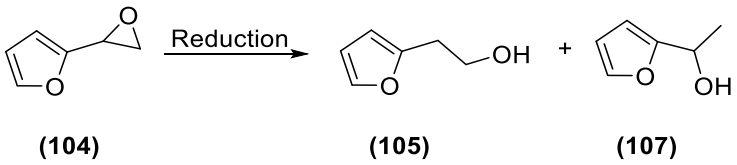


*Scheme 3.12: Epoxidation of furfuryl **(52)** to give the epoxide derivative **(104)**.*

3.3.5 Reduction:

It is well known that unsymmetrical epoxides afford mixtures of isomeric alcohols, and the product ratios are strongly dependent on the reducing agents employed.[120] For example, a combination of a hydride reagent (e.g., $NaBH_4$ or $LiAlH_4$) and a Lewis acid such as $AlCl_3$, zinc borohydride supported on silica gel and $AlPO_4$, and aluminum oxyhydroxide produces the least substituted alcohols; however, a disadvantage of these reaction methods is the poor selectivity to the desired product. A mixture of primary and secondary alcohols and other by-products are obtained, requiring subsequent purification to give the desired product in poor yields.[120]

Three different reducing agents were tested in the nucleophilic ring opening of furyl-2-oxirane **(104)** (Scheme 3.13, Table 3.2).



*Scheme 3.13: Reduction of the epoxide **(104)** to afford the primary alcohol derivative **(105)**.*

*Table 3.2: Attempts to reduce the epoxide **(104)** to afford the alcohol derivatives.*

Entry	Reductant	Solvent	Temperature (°C)	Time (h)	Products' yield (105)	(107)
1	$NaBH_4$	EtOH	rt	18	49%	27%
2	Red-Al	THF	0-25	3	0	13%
3	Pd/C 10%	MeOH	45	2	0	0

When sodium borohydride ($NaBH_4$) was used as reported,[121] the desired primary alcohol **(105)** was afforded with 49% yield and the secondary alcohol **(107)** with 27% yield. We think that to afford a better selectivity we need a counter-ion that is more strongly coordinating to oxygen such as $LiAlH_4$ to promote S_N1 type ring opening.

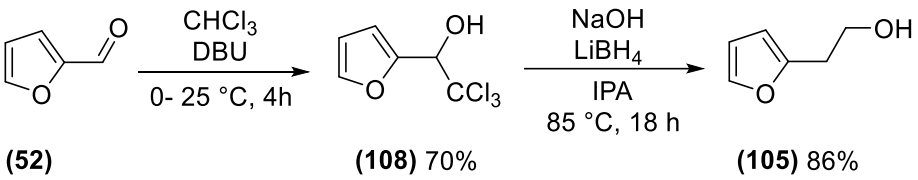
Next, sodium bis(2-methoxyethoxy)aluminium hydride (Red-Al) was used. The Red-Al attacked the less substituted carbon, so the main product was the secondary alcohol with low yield (Table 2). No reaction was found when palladium on carbon was used as a reducing agent with ammonium formate.

The opening of an epoxide under basic conditions follows a mechanism similar to an S_N2 reaction. The nucleophile attacks the least substituted carbon of the epoxide, leading to stereochemical inversion at this position. This is followed by a proton transfer from the weakly acidic solvent (ROH) to the resulting alkoxide, yielding a neutral alcohol.

The next stage of this reaction scheme was ring opening and subsequent ring closure, which affords the desired 7-membered ring through an internal redox isomerisation process.

3.3.6 Reduction of Aldehydes Involving a Jocic-Type Reaction:

(Trichloromethyl)carbinols, formed in one operation from either alcohols or aldehydes, can be converted into primary alcohols in a Jocic-type reaction involving $LiBH_4$.[123] First, the reaction between chloroform and furfural can be promoted using basic catalysts such as cyclic amidines (1,8-Diazabicyclo[5.4.0]undec-7-ene – DBU) with a slight excess of $CHCl_3$ without solvent provided a quantitative yield of the trichlorocarbinol derivative (Scheme 3.14). Then, the Jocic-Reeve reaction involves the deprotonation of a trichloromethyl carbinol, by base in protic media (2- propanol, IPA as a solvent) to generate a reactive gem-dichloro epoxide intermediate. A hydride source from $LiBH_4$ acted as the preferential nucleophile toward this epoxide to afford an α-substituted acyl chloride intermediate (yield 70%). Then, the acyl chloride subsequently undergoes reduction to generate the primary alcohol as a desired product, 2-(furan-2-yl)ethanol. The Jocic-Reeve reaction was carried out using three equiv. of NaOH and 4 equiv. of $LiBH_4$ and IPA at 85 °C for 18 h to afford the desired product at 86% yield.



*Scheme 3.14: Reduction of furfural Involving a Jocic-Type Reaction to afford **(105)***

This sequence offered a net one-carbon reductive homologation of aldehydes and a step-economical one-carbon homologation of primary alcohols. The desired product will be used towards a 7-membered ring of the desired lactone.

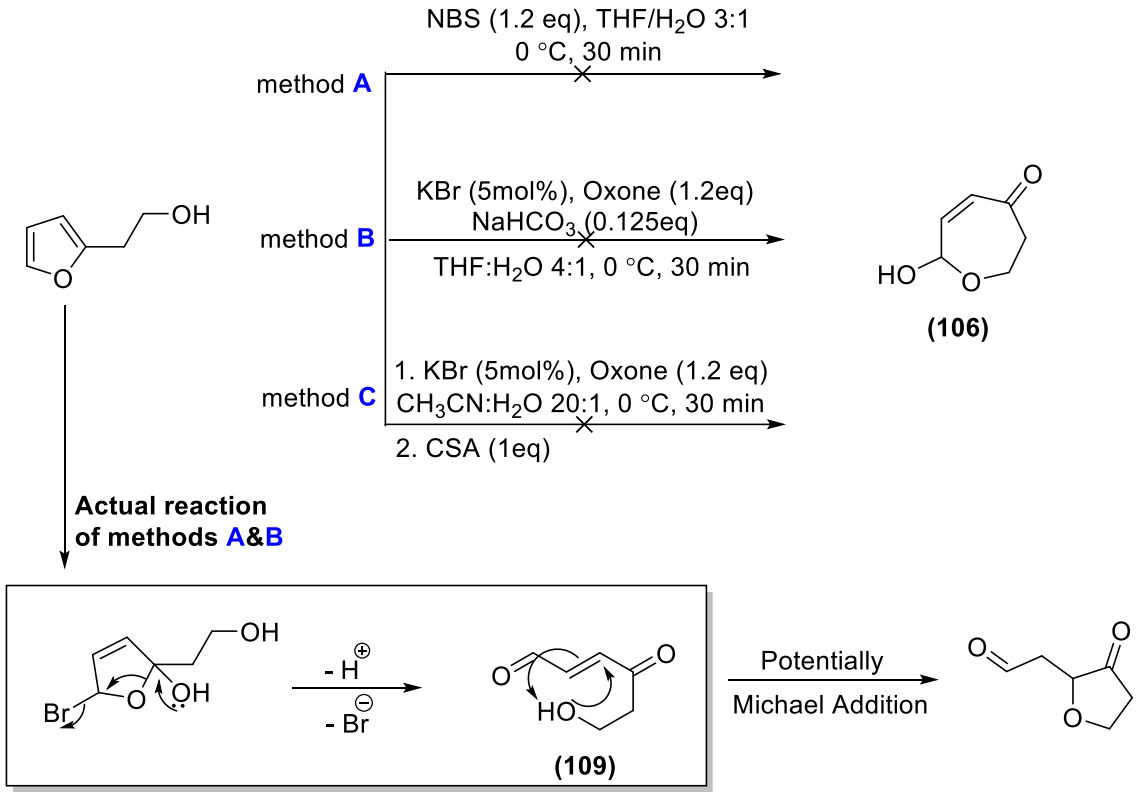
3.3.7 Oxidation towards 7-member Ring:

The Achmatowicz rearrangement (AchR) described above is an oxidative ring-expansion rearrangement of functionalised furfuryl alcohols into densely functionalised dihydropyranone acetals. AchR can be carried out using several oxidation techniques. Among these techniques, NBS stands out as the most commonly used oxidant due to its ease of use, compatibility with various functional groups, and consistently high yields in most instances. However, the primary disadvantage of this method is the production of stoichiometric organic byproduct (succinimide), which typically necessitates removal via column chromatography.[110]

Here, the ring expansion (ring opening and subsequent ring closure) of the alcohol **(105)** into (**106)** was investigated by three methods using Achmatowicz rearrangement.

Initially, *N*-bromosuccinimide (NBS) was used as an oxidant with a solvent mixture THF/H_2O (3/1) at 0 °C for 30 minutes (method A – Scheme 3.15). However, the desired product was not obtained. Secondly, the protocol of Guodong Zhaoa and Rongbiao Tong was explored using (KBr/oxone) in two different conditions.[110] First, KBr (5 mol%) and oxone (1.2 equiv.) in $NaHCO_3$ and THF/H_2O (4/1) at 0 °C for 30 minutes. However, this also did not afford the

desired product. The solvent mixture is critical to this reaction, so we applied another reaction conditions. Here, the solvent mixture was changed to CH_3CN/H_2O (20/1) and 10-camphorsulfonic acid (CSA) was added. Unfortunately, the reaction was not initiated. By analysing the ^1H NMR spectra of the products obtained from methods A and B, we found product **109** (Scheme 3.15 and Figure 3.1). A silica column purification was attempted on this product (**109**), but the product was decomposed. In another attempt, CSA was added to the crude version of **109** to obtain the 7-membered ring, but the compound was also decomposed. 7-membered rings have less bond angle strain than 3- and 4-membered rings but suffer from torsional and transannular strain, making them less stable than 5- and 6-membered rings, and this may explain the challenge of obtaining this ring by this synthetic route.[110]



*Scheme 3.15: Three methods A, B and C of oxidising (**105**) as attempts to afford (**106**). However, the obtained product was (**109**), which can be potentially converted via Michael Addition.*

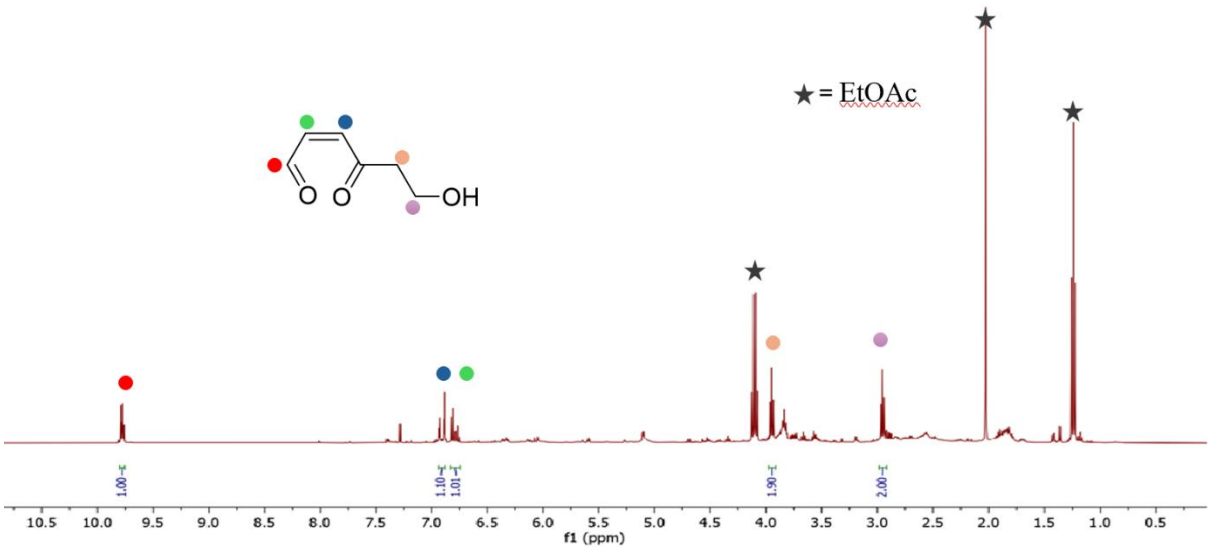
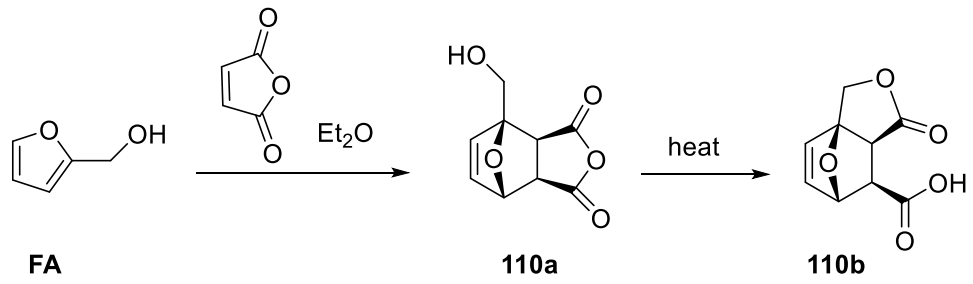


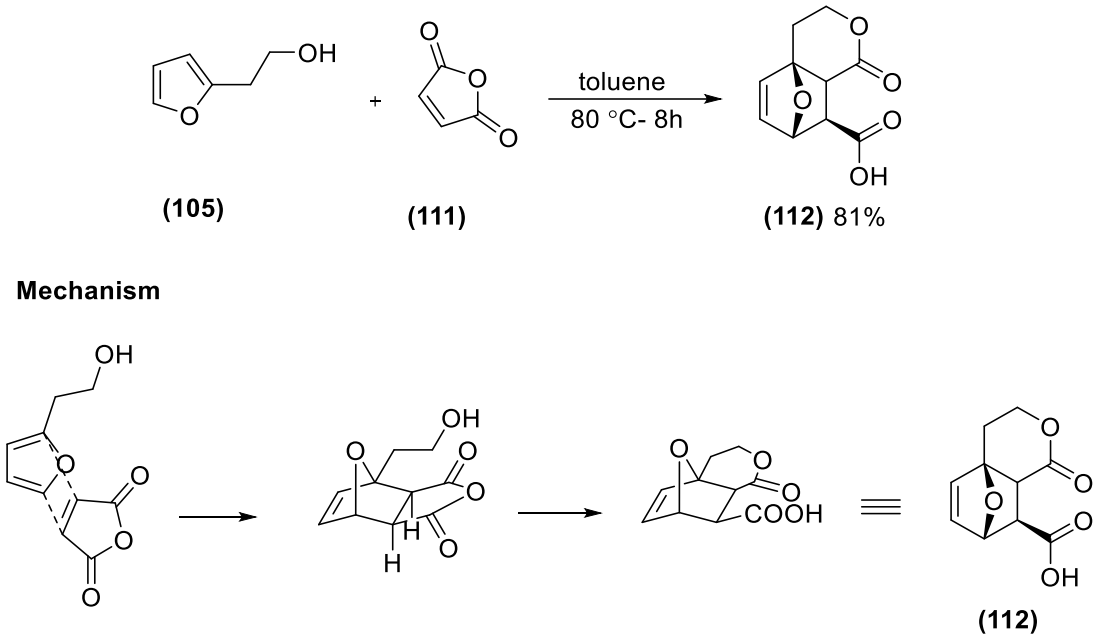
*Figure 3.1: The [1]HNMR spectrum of the obtained crude product (**109**) from oxidising (**105**) using methods A and B.*

3.3.8 Towards lactone-carboxy derivatives:

Furfuryl alcohol (**99**) is reported to react with maleic anhydride via intermolecular Diels–Alder reaction to yield an unstable adduct, reported as having structures (**110 a**) on the basis of the formation of a monoacetate. This undergoes irreversible intramolecular cyclisation during storage or warming, yielding the corresponding thermodynamically stable lactone 2-exo (**110 b**) (Scheme 3.16).[124]



Scheme 3.16: Formation of lactone 2-exo after DA reaction of FA with maleic anhydride.



*Scheme 3.17: The reaction of **105** with **111** via intermolecular Diels–Alder reaction including the mechanism.*

Here, we investigated this reaction using 2-(furan-2-yl)ethan-1-ol (**105**) which was carried out in toluene as a solvent for 8 h at 80 ℃ to afford the desired *exo*-product at 81% yield. This novel reaction route provided a novel product of (4aS,7R,8S)-1-oxo-1,3,4,7,8,8a-hexahydro-4a,7-epoxyisochromene-8-carboxylic acid (**112**) (Scheme 3.17). The product was characterised by ^{1}H, ^{13}C NMR, MS and IR. The absence of the carbonyl of maleic anhydride and having two carbonyls represent the lactone and the carboxylic acid, confirming the structure of the desired product.

3.4 Conclusions:

Furfural, as a biomass chemical, is a promising platform to manufacture products such as polymers and their monomers. In this chapter, several chemical modifications were applied to

furfural to obtain furfural dervatives with different functional groups; alcohol (**99**, **105**), lactone (**102**, **112**), epoxide (**104**), and carboxyl groups (**112**).

The Achmatowicz rearrangement (AchR) was used as an oxidative ring-expansion rearrangement of functionalised furfuryl alcohols to densely functionalised dihydropyranone acetal (**100**), which converted to the lactone derivative (**102**). This lactone can be used to produce functionalisable novel polyester via ring-opening polymerisation. The alkene group of the backbone of the potential polyester can be utilised by post-polymerisation modifications.

AchR with 2-(furan-2-yl)ethanol (**105**) to afford the potential seven-membered ring (**106**) was not successful. The reaction yielded another thermodynamically stable product (**109**).

A novel bicyclic product (**112**) was made via the Diels–Alder reaction utilising furfural and maleic anhydride. This potential monomer has four functional groups (alkene, epoxide, lactone, and carboxylic) and two polymerisable groups (lactone and carboxylic). Hence, it can be used to produce novel polyesters via ring-opening polymerisation and polycondensation. The alkene and epoxide groups can also be modified pre- and post-polymerisation.

Chapter Four:

4. Polymerisation:

4.1 Introduction:

Polymerisation is the chemical process of bonding monomer building blocks to form larger molecules, which can range from a few monomers (oligomers) to hundreds or thousands of monomers (polymers). Commercial polymers typically consist of thousands of repeating units. These repeating structures give rise to a diverse range of natural and synthetic materials, each with distinct physical, chemical, thermal, and mechanical properties. Polymers can be naturally occurring, such as cellulose and proteins, or synthetic, like plastics (e.g., polyethylene, polystyrene). Their molecular structure allows for customisation of properties, making them essential in various industries, including medical devices, packaging, electronics, and wound care. Their widespread use is attributed to key characteristics such as lightweight nature, high strength, flexibility, and resistance to chemical corrosion.[125] For example, in wound care, hydrogels, polyurethane foams, and bioresorbable polymers are often used for advanced wound dressings that promote healing.[126] Polymers have also seen significant advancements in drug delivery systems and biocompatible materials.[126]

The polymer can be written to show the number of repeat units. For example, polyethylene can be written like this $–[–CH_2–CH_2–]_n$, a unit of ethylene between square brackets using a number or a letter, like in this case, *n*, representing the average quantity of mers present in this polymer. The degree of polymerisation, also known as DP, refers to the average number of repeat units in the polymeric chain.[125] A linear polymer is the simplest form, with units connected in a linear sequence like beads on a string. Alternatively, a polymer can be branched, with branches

varying in length. For example, low-density polyethylene can have both short and long branches. Linear and branched molecules are depicted in Figure 4.1a, b. Branched polymers can also take the form of star- or comb-shaped structures (Figure 4.1c, d). In addition, polymers can be double-stranded, known as ladder polymers (Figure 4.1G), or have semi-ladder structures (Figure 4.1E). Interconnected branches of different polymers can form network structures, with planar networks resembling the structure of graphene, honeycomb lattices, or 2D polymer sheets.[127]

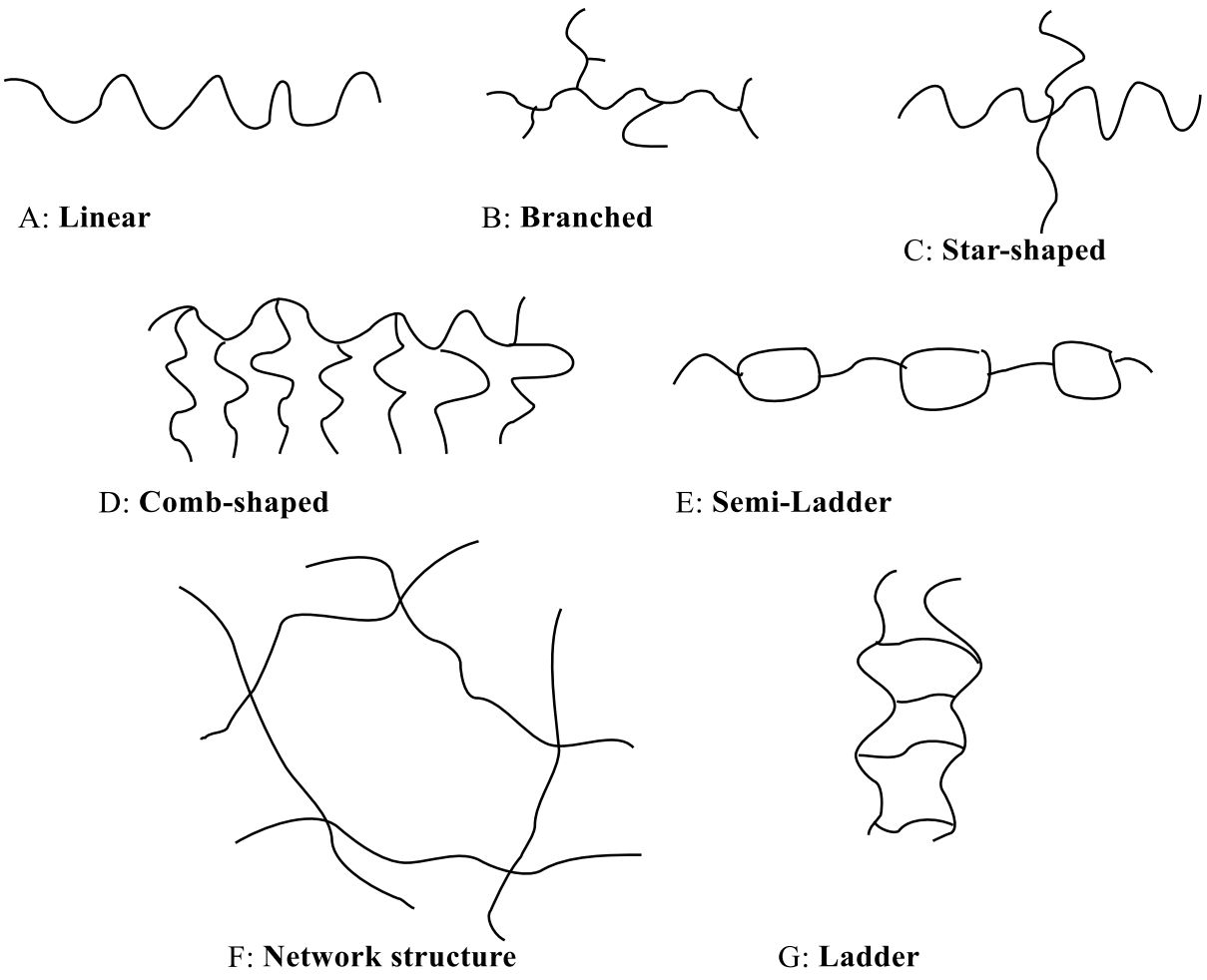


Figure 4.1: Shapes of polymer molecules.

A network polymer is shown in Figure 4.1F. The term polymer can be applied to molecules made up of either single repeating structural units, like polyethylene, made from ethylene only,

or from different ones. If there are two or more structural units, the term copolymer is used. An example would be a copolymer of ethyl methacrylate and styrene.[125]

Copolymers can exist in linear or branched forms. If there is a consistent repetition of structural units and this repetition alternates, the copolymer is referred to as an alternating copolymer. If there is no such regularity, it is categorised as a random copolymer. Apart from random and alternating sequences, there are also block copolymers composed of blocks of individual polymers connected by covalent bonds. The most common methods of polymerisations are chain-growth (addition) and step-growth (condensation) polymerisation.[125] In addition polymerisation, a chain reaction adds new monomer units to the growing polymer molecule one at a time through specific functional groups in the monomer. Each new monomer unit creates an active site for the next attachment/monomer. Two large groups of monomers form polymers via chain polymerisation.[128] These are monomers with multiple bonds, mostly vinyl compounds like styrene or methyl methacrylate and cyclic compounds used in ROP, such as epoxides, lactones, lactams, and carbonate.

Chain-growth polymerisations are characterised by the following key aspects:

1. The growth of the chains occurs through the repetitive addition of monomers to the reactive sites.

2. The monomer is utilised gradually and remains present throughout the polymerisation process.

3. Polymer formations involve two separate mechanisms: initiation and propagation.

4. Typically, there is also a termination phase in most instances.[129]

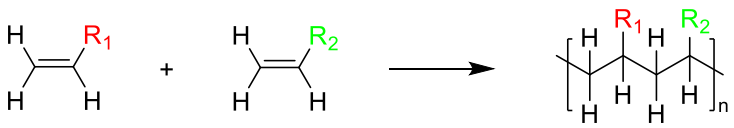
The other polymerisation method is condensation polymerisation, in which the reaction between monomer units and the growing polymer chain-end group releases a small molecule.

This reversible reaction will reach equilibrium and halt unless this small molecular by-product is removed. The important features of step-growth polymerisations are:

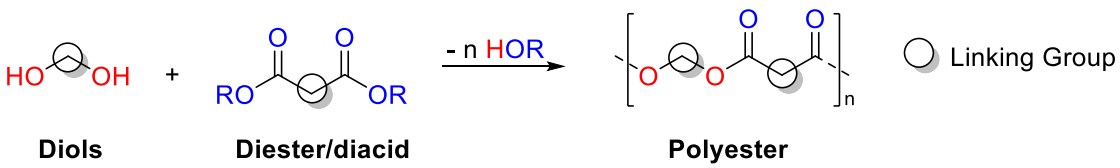
1. At the beginning of the reaction, the monomer is consumed early, while the increase in molecular weight happens gradually.
2. Polymeric chains grow through monomers, oligomers, and polymers reactions.
3. The end groups of the polymers remain continuously reactive throughout the polymerisation process, as there is no termination step.
4. The reaction mechanism remains consistent throughout the entire polymerisation process.[130]

The traditional method for producing polyesters and polyamides is polycondensation. Understanding the polymerisation process used to synthesise a plastic provides valuable insight into its properties and behavior. For instance, plastics formed via condensation polymerisation—a process in which a small molecule, such as water, is released—can be susceptible to degradation when exposed to water at high temperatures.

1- Addition Polymerisation



2- Condensation Polymerisation



Scheme 4.1: The two most common methods are chain-growth (addition) and step-growth (condensation) polymerisation.

Polyesters, such as polyethylene terephthalate (PET), can undergo hydrolysis, where the polymer chains are cleaved upon interaction with acidic, basic, or certain neutral conditions. This degradation process leads to a loss of the polymer's mechanical and chemical properties.[131]

Tacticity refers to the spatial arrangement of substituent groups along the backbone of a macromolecule. During the polymerisation of linear polymers, pendant groups can adopt either a regular, ordered configuration or an irregular, random arrangement. For example, when propylene undergoes polymerisation, it can form two distinct stereoregular structures or a non-stereoregular (atactic) arrangement. This principle also applies to other monosubstituted vinyl monomers. Polymers can exhibit isotacticity, where all chiral centres have the same configuration (Figure 4.2). Visualising the chain backbone drawn in the plane of the paper and all phenyl groups oriented above the plane (Figure 4.2a) helps in visualising isotactic polystyrene. Alternatively, the orderliness can involve every other chiral centre having the same configuration, known as syndiotactic (Figure 4.2b).

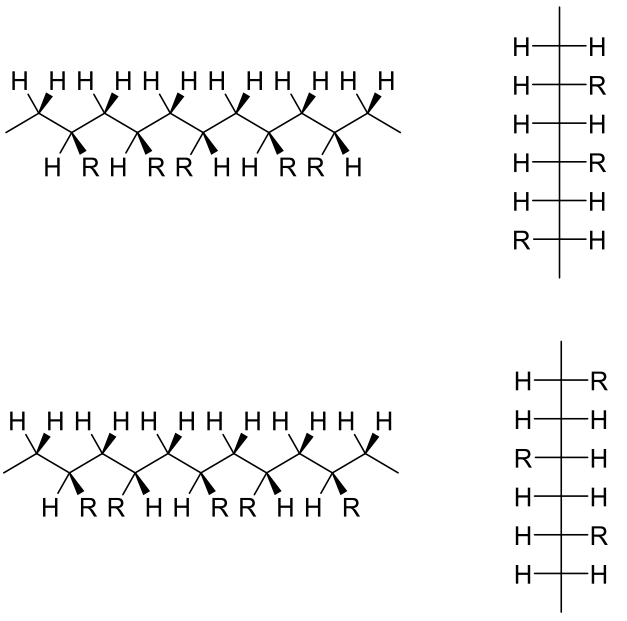


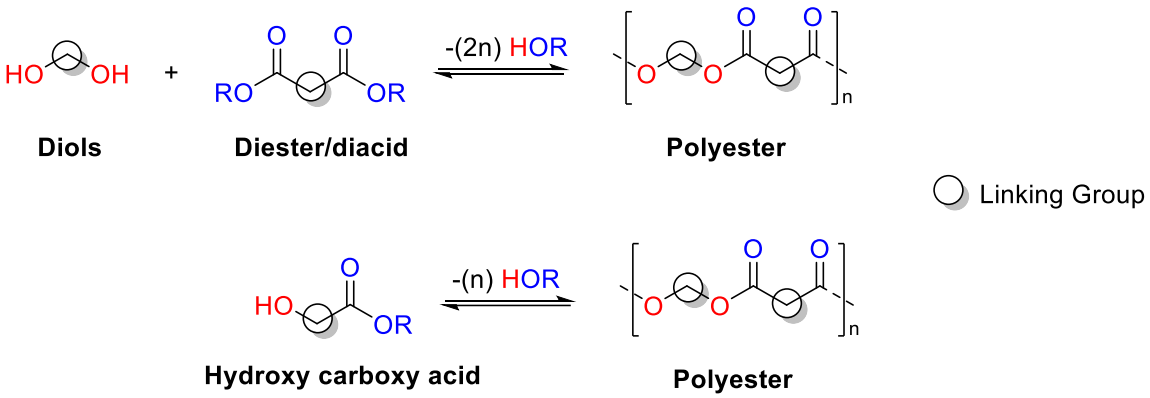
Figure 4.2: The steric arrangement in polymer; isotactic (top), syndiotactic (bottom), of substituted vinyl monomers.

A lack of orderliness or randomness in the steric arrangement is termed atactic or heterotactic. Stereospecific polymers can also be synthesised from 1,2-disubstituted olefins, resulting in diastereoisomers or ditactic polymers.[125] When the polymerisation reaction occurs in three dimensions, gelation occurs after progressing to a certain point. This clearly defined transition during polymerisation is referred to as the gel point. At this stage, the reaction mixture transforms from a thick liquid into a flexible gel. Prior to gelation, the polymer is both soluble and fusible. However, after reaching this stage, it becomes neither soluble nor fusible. This change occurs due to the restricting influence of three-dimensional network structures. Another way to categorise polymers is based on their ability to form crosslinked or gelled networks. The polymers that undergo gelation are termed thermosetting. These polymers are also known as cross-linkable polymers. Once gelation has occurred, increasing the temperature will not restore plasticity, as the molecules can no longer slide past one another. For the same reason, they can also no longer be dissolved in any solvent. Polymers that do not gel or crosslink are classified as thermoplastic. Such polymers can always be reshaped with the application of heat and can also be dissolved in suitable solvents.[125] In this work, we carried out two types of polymerisations: step-growth (polycondensation) and chain-growth (ring-opening polymerisation (ROP) and radical polymerisation).

4.2 Polycondensation:

Condensation polymerisations (polycondensations) involve stepwise reactions between bifunctional or polyfunctional components, releasing small molecules like water, alcohol, or hydrogen while forming macromolecular substances.[130] The identical principles apply when creating linear condensation polymers from bifunctional compounds as they do for polyfunctional compounds, which can produce branched, hyperbranched, or crosslinked

condensation polymers. Essentially, there are two main approaches to consider. One either starts from a monomer with two unlike groups suitable for polycondensation (AB type), or one starts from two different monomers, each possessing identical reactive groups that can react with each other (AABB type). An example of the AB type is the polycondensation of hydroxycarboxylic acids, and an example of the AABB type is the polycondensation of diols with dicarboxylic acids (Scheme 4.2).[130]



Scheme 4.2: Examples of polycondensation from two monomers (top) and one monomer (bottom).

The creation of a condensation polymer occurs through a stepwise mechanism. Therefore, the initial phase of polycondensation for a hydroxycarboxylic acid (AB type) involves forming a dimer with identical end groups to the original monomer. The end groups of this dimer can react in the subsequent step, either with the monomeric compound or with another dimer molecule, and this process continues. The molecular weight of the subsequent macromolecules steadily increases over time, in contrast to many addition polymerisations, such as radical polymerisations. The intermediates produced through separate, individual reactions are oligomeric and polymeric entities that retain the same functional end groups as the initial monomeric starting material.[130]

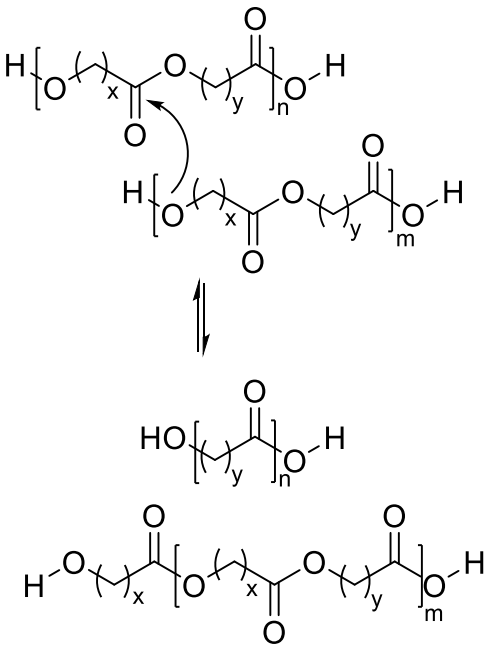
In principle, these intermediates can be isolated without losing their capability for further growth. Thus, all reactions can occur, where Mi, Mj denote oligomeric or polymeric species containing *i*, *j* monomeric units, respectively.

$$M_i + M_j \longrightarrow M_{j+i}$$

On this basis, the kinetics of polycondensation were established long ago. Several key factors are particularly noteworthy:

- Dependence of the average molecular weight on conversion,
- Dependence of the average molecular weight on the molar ratio of reactive groups,
- Influence of condensation equilibrium on both conversion and average molecular weight, and
- Exchange reactions, such as transesterification or transamidation.[132]

Examining the unreacted functional groups allows for straightforward monitoring of polycondensation progress.



Scheme 4.3: An example of transesterification between two polyester chains.

When the reactive groups are available in equimolar quantities, which is typically preferred, it is adequate to analyse just one of the two groups, such as the carboxyl groups, during polyester synthesis. The second factor that additionally affects polycondensations is exchange reactions, which can occur between free end groups and junction points in the chain, for example, between OH end groups and ester groups of a polyester (transesterification).[132] Neither the number of free functional groups or molecules nor the number-average degree of polymerisation is altered. Thus, two equalised macromolecules could react with one another to give one very large and one very small macromolecule; conversely, a very large and a very small macromolecule can be converted into two macromolecules of similar size. Independent of the initial distribution, these exchange reactions will, in each case, lead to a state of dynamic equilibrium in which the rates of formation and consumption of molecules of a given degree of polymerisation are equal.[132] This results in an equilibrium distribution of molecular weights formally the same as that of random polycondensation. Therefore, the exchange reactions will not affect the molecular weight distribution in normal polycondensations.

Finally, the formation of macrocyclic oligomers and polymers must be addressed. For example, mass spectrometry elucidates the existence of ring-shaped polycondensates in all types of polycondensates.

Some additional factors must be considered if one wishes to attain high molecular weights in polycondensations. Firstly, the condensation reaction must be specific and proceed with the highest conversion. Otherwise, only mixtures of oligomers will be obtained. Furthermore, for polycondensation reactions in which two or more components may participate, care must be taken to ensure strict equivalence in the proportions of the reacting groups throughout the reaction. The equilibrium position of the reaction must be displaced as far as possible towards condensation. In a manner similar to the condensation of monofunctional compounds, this can

be accomplished by eliminating the low-molecular-weight byproduct, such as water, as thoroughly as possible from the reaction mixture. This can be achieved through high vacuum distillation or azeotropic distillation. Passing very dry inert gas through the well-stirred reaction mixture is advantageous in facilitating the diffusion of the eliminated component from the viscous solution formed during polycondensation. High demands are placed on the purity of the starting materials. They must be free from monofunctional compounds since these blocks the end groups of the resulting macromolecules, preventing further condensation. Only bifunctional compounds, in the presence of appropriate catalysts, can produce linear condensation polymers, as polyfunctional compounds tend to result in branching, hyperbranched structures, or cross-linking.[132]

In the case of polylactic acid (PLA), polycondensation of lactic acid by connecting carboxyl and hydroxyl groups produces water byproducts simultaneously. Because of the challenges in completely eliminating byproducts from the thick reaction mixture, the polymer created via direct polycondensation typically has a low molecular weight (less than 50,000 $g \cdot mol^{-1}$) and low quality. Numerous newly developed polycondensation methods have been proposed to overcome this main disadvantage. In recent years, azeotropic polycondensation (AP) and solid-state polymerisation (SSP) have two main directions. For the AP approach, the water is removed efficiently by appropriate azeotropic solvents, by which the equilibrium between monomer and polymer is manipulated in an organic solvent to produce a polymer with relatively high molecular weight in one step. Besides, the temperature applied is allowed to be lower than the polymer melting point, avoiding impurities caused by depolymerisation and racemisation. Therefore, an appropriate solvent is critical to performance conditions and polymer properties.[133]

Solid-state polymerisation (SSP) consists of two stages:

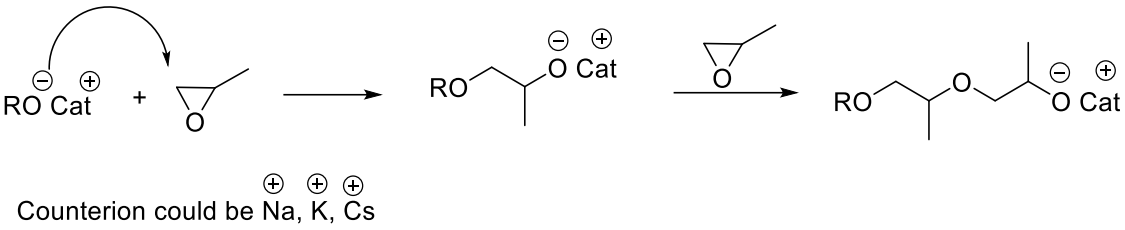
1- Melt-phase polymerisation, where oligomers are produced at high temperatures (150–200 °C).
2- Solid-state polymerisation, which further increases the molecular weight at a temperature between the glass transition temperature (T_g) and the melting point (T_m).

In the second stage, the prepolymer—with a relatively low molecular weight—exists as a semi-crystalline powder, chip, pellet, or fiber. It is typically pulverised and thoroughly dried before heating to ensure efficient and uniform heat transfer among the dried particles, facilitating the growth of high-molecular-weight polymers. Additionally, since cyclisation, decomposition, and other side reactions are minimised at lower temperatures, SSP polymers generally exhibit enhanced properties and higher purity.[133]

4.3 Ring-Opening Polymerisation:

In ROP, monomers are cyclic, mostly heterocyclic, and polymerisation requires ring opening, preceding the addition of the monomers to the growing macromolecules. Almost all ROPs occur via ionic reactions since opening the bond between the heteroatom and carbon atom involves groups that differ substantially in their electronic structures. These include cyclic ethers, cyclic sulfides, cyclic acetals, cyclic esters (lactones), cyclic amides (lactams), and cyclic amines.[134]

An alcoholate anion (alkoxide anion) initiates the anionic polymerisation of propylene oxide, and ring-opening regenerates the anion, which becomes the active species. This is shown in Scheme 4.4.



Scheme 4.4: The Anionic polymerisation of propylene oxide.

There are two mechanisms of ROP, ionic and pseudo ionic. In the latter, ROP proceeds with the formation of multicenter-growing species without forming ions. The ionic group has two subgroups: anionic and cationic ROP (AROP and CROP). Various Lewis and protic acids are capable of initiating cationic polymerisation of epoxides. Among them, the following metal salts are effective in the polymerisations of ethylene and propylene oxides: $ZnCl_2$, $AlCl_3$, $SbCl_5$, BF_3, BCl_3, $BeCl_2$, $FeCl_3$, $SnCl_4$, and $TiCl_4$. Often these polymerisations can be carried out in bulk without any solvent.[134]

In anionic polymerisation, both initiation and propagation involve alcoholate or carboxylate anions. Thus, the polymerisation of ethylene oxide, propylene oxide, or ε-caprolactone is initiated and then propagates on alcoholate anions. In these reactions, polymer growth occurs via a nucleophilic attack on the monomer. However, reactions involving strong bases, such as sodium hydroxide (NaOH), potassium hydroxide (KOH), or alkoxides, typically result in low molecular weight polymers. This is because these bases not only initiate polymerisation but also facilitate uncontrolled chain transfer and termination reactions, preventing the formation of high-molecular-weight polymers. [134] The initiation, an S_N2 displacement, forms an alkoxide ion: An ion-pair in contrast to free ions. An ion pair is electrically neutral. $Cat^{\oplus}$ is a cationic counterion; often $Na^{\oplus}$, and $K^{\oplus}$ cations are used.[134]

In the AROP of cyclic esters, there is an extensive chain transfer: intramolecular – i.e., within the macromolecule – and intermolecular – to the other macromolecules. Both lead to chain

rupture. In the former, this will lead to cyclic formation, and in the latter, only change the molar mass distribution. In the intermolecular process, the number of macromolecules does not change, thus M_n is invariant and only M_w changes. This is because two macromolecules are interacting: one macromolecule attacks another one, and, as a result, two macromolecules are formed. The extent of intermolecular chain transfer depends on conversion and may also proceed when propagation is over.[134]

There is also chain transfer to the low molar mass chain transfer agents, either adventitiously present or added intentionally to introduce required end groups. For instance, chain transfer to an alcohol in AROP of ethylene oxide. There are also termination reactions involved in chain transfer.[134]

ROP proceeds (mostly) exothermically because cyclic monomers are usually strained species.[134] Due to their geometry, certain bond angles are known to be free of strain. Ring-opening polymerisation (ROP) has several advantages over polycondensation, including:

- No by-products: ROP doesn't produce by-products like methanol or water.
- Low temperatures and pressure: ROP reactions occur at lower temperatures and atmospheric pressure.
- ROP is a relatively quick process.
- ROP is well suited for making fibre-reinforced thermoplastic composites.
- Functional groups: Radical ROP can produce polymers with functional groups in the backbone chain, such as ethers, esters, amides, and carbonates, which makes these polymers useable for post-polymerisation modification.
- Wide range of monomers: ROP can polymerise a wide range of cyclic monomers, including lactones, lactides, cyclic carbonates, siloxanes, and ethers.

- Chemically recyclable polymers: ROP can generate polymers that undergo ring-closing depolymerisation, allowing them to be recycled back into their monomeric form.[134]

4.4 Radical Polymerisation:

The formation of macromolecules from vinyl monomers proceeds by multiple reactions of double bonds in a series of identical reactions, starting from initiation and then chain growth. Initiation involves the reaction of a compound with an unpaired electron, very often resulting from low-energy dissociation of a given radical initiator. This radical (R•) reacts with the first monomer molecule. Then, the addition of the next monomer additions leads to the formation of a macromolecular radical. After a certain number of propagation steps, the reaction between two macroradicals leads to the termination of polymer growth. This process is known as the termination reaction. However, in polymerisations where the reactive species are ions—which cannot recombine to form covalent bonds—termination typically occurs through side reactions rather than direct recombination. In radical polymerisation, the rate of propagation (R_p) is equal to the rate of polymerisation (R_{pol}), as nearly all monomer molecules are consumed during the propagation step.[135]

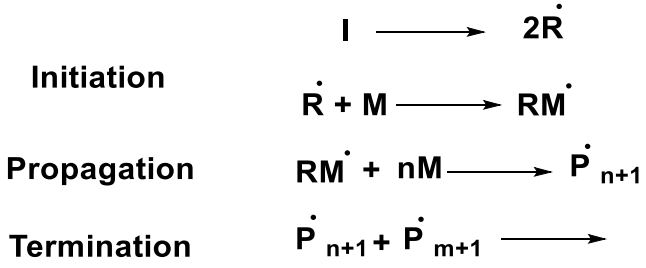


Figure 4.3: Kinetic Relationships in Free-Radical Polymerisations.

Significant efforts have been made to create polymers directly from terpenes because their structures contain alkene moieties that offer the opportunity for facile polymerisation via free

radical routes using readily accessible conditions. However, extensive research has shown that the terpenes do not easily homopolymerise. Even in the presence of a co-monomer (such as styrene or an acrylate), the level of incorporation of e.g. β-pinene or D-limonene is minimal. The polymers produced thus far have only very low molecular weights.[88]

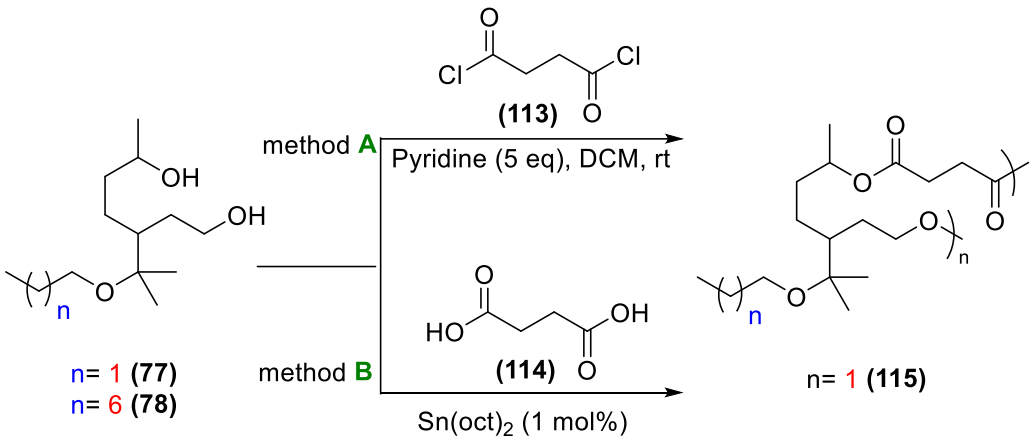
4.5 Aims and Objectives:

In this chapter, we will polymerise some of the monomers synthesised in Chapters 2 and 3 using three polymerisation methods: polycondensation, ring-opening polymerisation, and radical polymerisation. Additionally, we will determine the molecular weight and glass transition temperatures of the resulting polymers.

4.6 Results:

4.6.1 Polycondensation of α, and β-pinene derivatives:

Polyesters can be made by utilising the diol derivatives of α-pinene that were synthesised in chapter two (**77** and **78**). These two monomers have two hydroxy groups and differ in the length of the side group (n = 1 or 6).



*Scheme 4.5: Copolymerisation of diols 77 and **78** with diacids **113** and **114** using two methods A and B.*

*Table 4.1: Conditions and results of copolymerisation of diols 77 and **78** with diacids **113** and **114** using two methods A and B.*

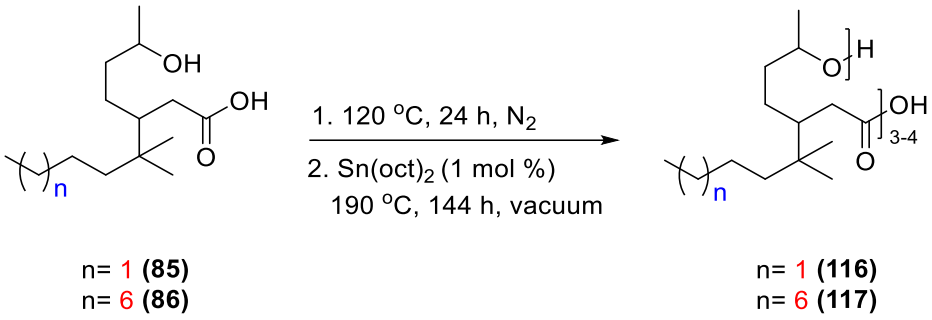
Entry	Monomer n=	Method	Temperature (°C)	Time (h)	M_n (g/mol)	Đ
1	1	A	rt	24	-	-
2	1	A	rt	96	1500	1.40
3	6	A	rt	24	-	-
4	1	B	120-150	1	-	-
5	1	B	120-150	5	700	2.22

Polyesters can be obtained by polycondensation of these monomers with dicarboxylic monomers such as succinyl chloride (**113**) or succinic acid (**114**) (Scheme 4.5, methods A and B), and these will produce by-products of HCl and water, respectively. Equivalents of **113** and **114** were used with monomers **77** and **78**. In method A, the reactions (Table 4.1, entries 1 - 3)

were carried out in 5 mol. equivalent of pyridine as a basic catalyst to promote the esterification and dichloromethane as a solvent at ambient temperature. The polymerisation was not initiated for 24 hours (entries 1 and 3), but leaving the reaction for 96 hours resulted in a low molecular weight of polymer at M_n of 1500 g/mol and 1.4 dispersity (Đ). The conversion was not completed as the ^{1}HNMR spectrum confirmed the presense of the starting monomer. However, the stirrer bar of the reaction could not be stirred further as the resulting polymer made an elastic material. In method B, these reactions were carried out using bulk polymerisation, with $Sn(oct)_2$ (1%) as a precatalyst at 120 °C to 150 °C under vacuum (Table 4.1 entries 4 and 5). The polymerisation mechanism of stannous octanoate $Sn(Oct)_2$ is thought to be a coordination-insertion process. First, tin(II) alkoxide is formed with the hydroxy of the monomer. Then, the carbonyl of the carboxy acid of the monomer coordinates with the tin atom. After that, a nucleophilic attack of -O-Sn- attacks the carbonyl. This form of propagating species, monomer-O-Sn-O-, so the other monomers are inserted into this species into the reactive Sn-O bond. Initially, the polymerisation was attempted for one hour (Table 4.1, entry 5). ^{1}H NMR analysis after one hour indicated that the concentration of the starting monomer had not changed. However, after 24 h, the relative concentration of (**77**) began to decrease, and resonance at approximately 4.69–4.93 ppm emerged, indicating the formation of the polyester (**115**). At this stage, the vacuum was applied to drive the polymerisation to high conversion and remove water from the reaction mixture. GPC analysis revealed that a significant portion of the reaction mixture consisted of low molecular weight oligomers, with molecular weights up to 700 g/mol. ^{1}H NMR analysis suggested that the reaction had gone to full conversion.

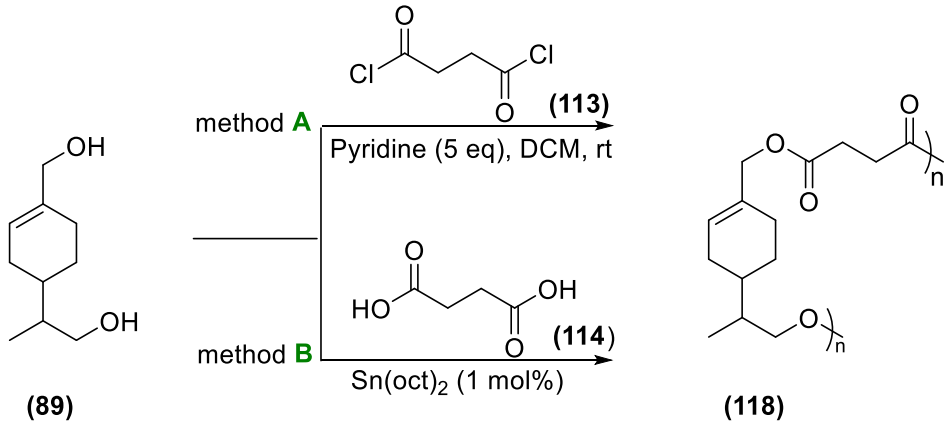
We also explored the potential polymerisation route of the hydroxy-carboxy derivatives of α-pinene. Both (**85**) and (**86**) were dried initially at 120 °C under nitrogen for 24 hours to remove any traces of moisture which may interfere with the polymerisation. After that, the attempt at

polymerisation was carried out using bulk polymerisation, with $Sn(oct)_2$ as a catalyst at 190 °C under vacuum for 144 hours (Scheme 4.6). This reaction resulted in novel low molecular weights of polyesters (**116** and **117**) at a degree of polymerisation of four monomer units for **116** and three monomer units of **117** as viscous materials. The molecular weights were confirmed by the MS.



*Scheme 4.6:Polymerisation of hydroxy-carboxy monomers **85** and **86** by $Sn(oct)_2$*

Polyesters can also be made by utilising the diol derivatives of β-pinene synthesised in chapter two (**89**). This monomer has two hydroxy groups, so again, polycondensation of this monomer with equivalents of dicarboxylic monomers, such as succinyl chloride (**113**) or succinic acid (**114**) (Scheme 4.7, methods A and B), will provide polyesters and by-products of HCl and water, respectively.



*Scheme 4.7: Copolymerisation of diols **89** with diacids **113** and **114** using two methods A and B.*

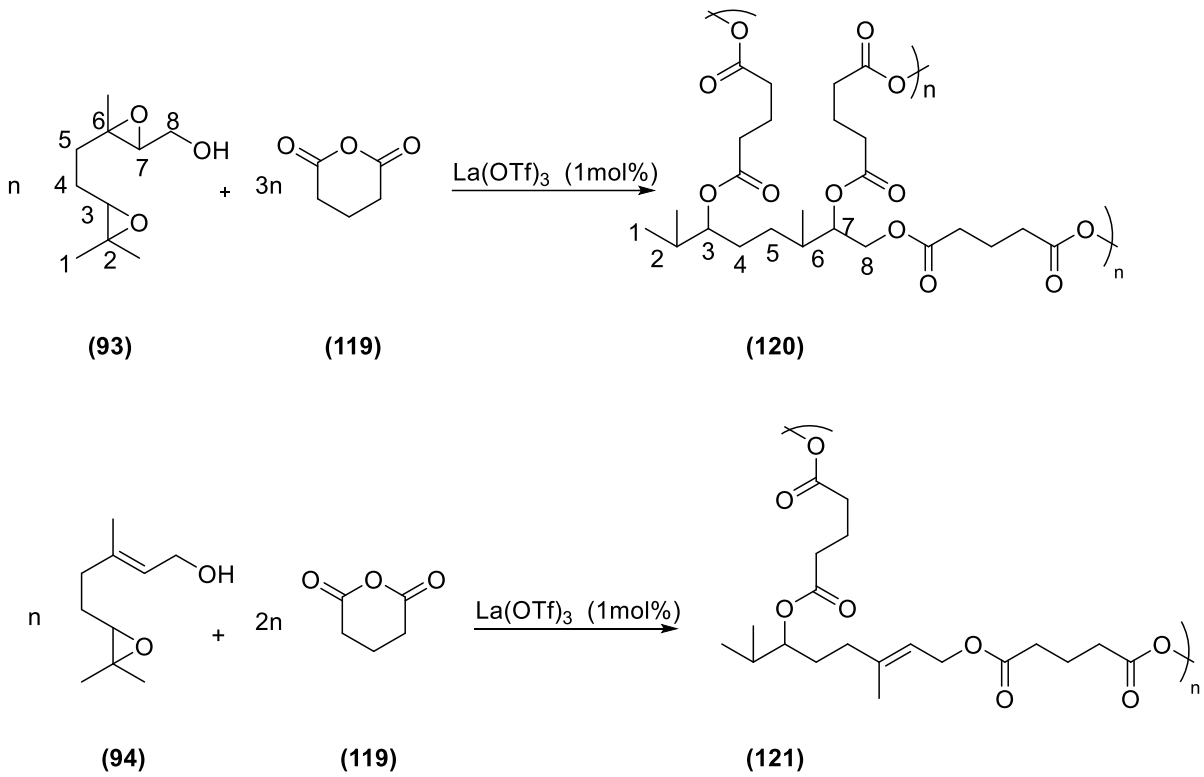
*Table 4:2: Conditions and results of copolymerisation of diols **89** with diacids **113** and **114** using two methods A and B.*

Entry	Method	Temperature (°C)	Time (h)	M_n (g/mol)	Đ
1	A	rt	24	-	-
2	A	rt	96	3200	2.90
3	B	120-150	24	8400	4.02

In method A, the reactions (Table 4:2, entries 1 - 2) were carried out in 5 equivalent of pyridine as a basic catalyst to promote the esterification and dichloromethane as a solvent at ambient temperature for 24 and 96 hours. The polymerisation was observed after 96 hours to give a polymer of 3200 g/mol and a dispersity of 2.90. When method B is used, the reaction was carried out using bulk polymerisation, with $Sn(oct)_2$ as a precatalyst at 120 °C to 150 °C under vacuum remove water from the reaction mixture (Table 4.2 entries 3). The monomer consumption was followed by ^1H NMR. After 24 h, the reaction mixture became viscous, and the stir bar was stopped to indicate polymerisation. GPC analysis revealed molecular weights of up to 8.4 kDa of a novel polyester (**118**) with broad dispersity at 4.02 Đ. The broad dispersity is likely because of the transesterification. ^1H NMR analysis suggested that the reaction had gone to full conversion.

4.6.2 ROP of Geraniol and furfural derivatives:

Polyesters synthesised through the co-polymerisation of epoxides and cyclic anhydrides compose a growing class of polymers that exhibit an impressive array of chemical and physical properties. Di-epoxides (**93**) and mono-epoxide (**94**) of geraniol derivatives were synthesised in chapter two and are suitable for ring-opening polymerisation (ROP). These two monomers reacted with different equvalents of glutaric anhydride (**119**) in the presence of lanthanum trifluoromethanesulfonate ($La(OTf)_3$) as a catalyst for copolymerisation (Scheme 4.8).



*Scheme 4.8: Copolymerisation of geraniol epoxides derivatives **93** and **94** with glutaric anhydride to polyesters.*

The reactions were carried out either in toluene or tetrahydrofuran (THF) as solvents at different temperatures from 25 to 80 °C at 72 to 120 hours (Table 4.3). All reactions resulted in a range of various molecular weights of polymers from 660 Da (oligomers) to 3800 Da.

*Table 4.3: Conditions and results of copolymerisation of geraniol epoxides derivatives **93** and **94** with glutaric anhydride **119***

Entry	Geraniol epoxide	(119) (x eq.)	Solvent	Temp. (°C)	Time (h)	M_n (g/mol)	Đ
1	**(93)**	2	Toluene	25	120	-	-
2	**(94)**	1	Toluene	25	72	2350	1.32
3	**(93)**	2	Toluene	80	72	2400	1.40
4	**(94)**	1	Toluene	80	72	2720	1.55
5	**(93)**	2	THF	60	120	660	1.80
6	**(94)**	1	THF	60	120	3800	1.22

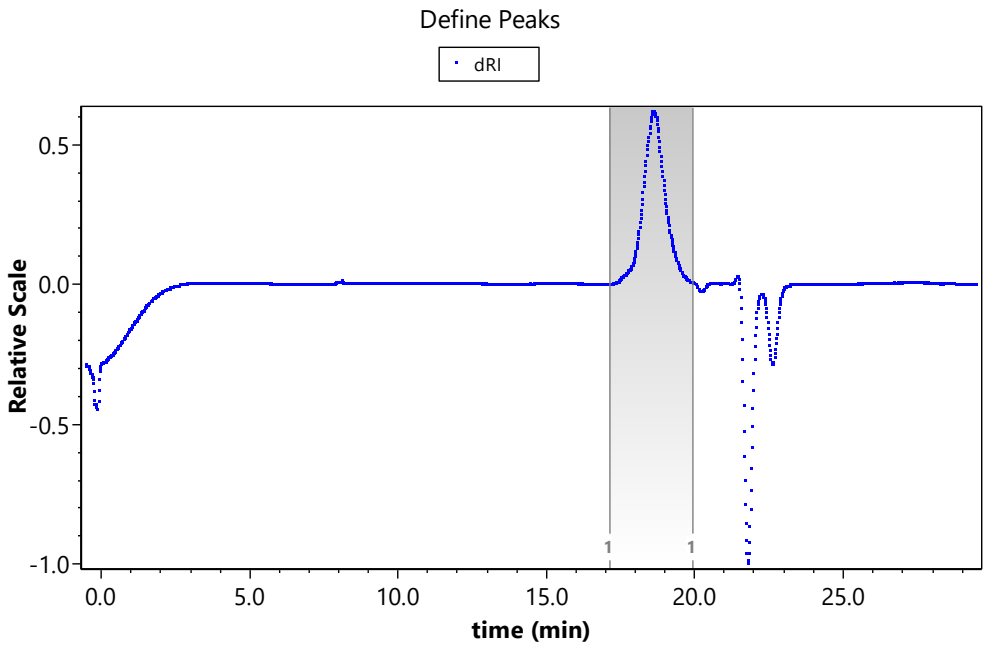


Figure 4.4: GPC chromatogram (refractive index) of entry 6 of table 4.3.

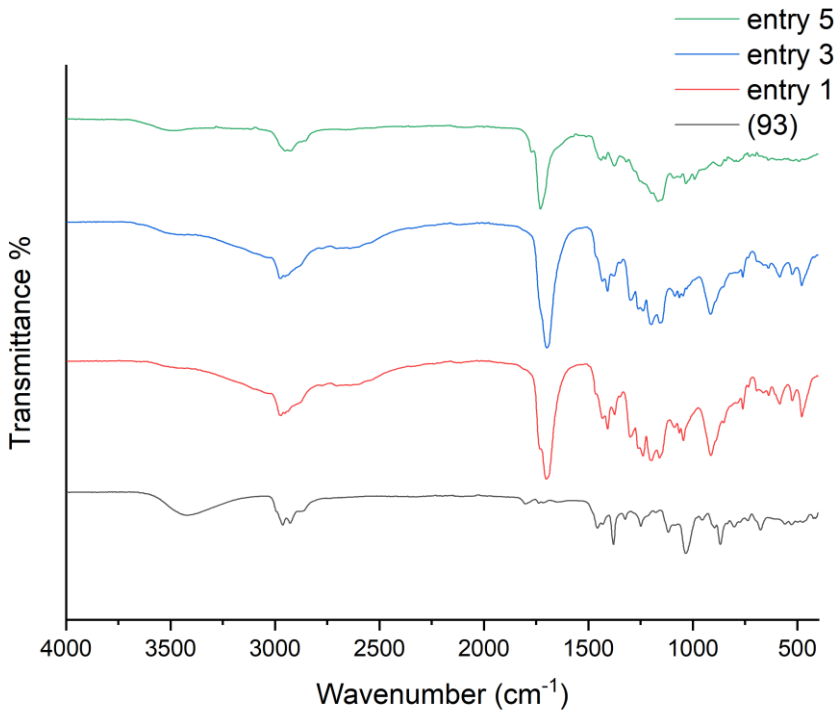
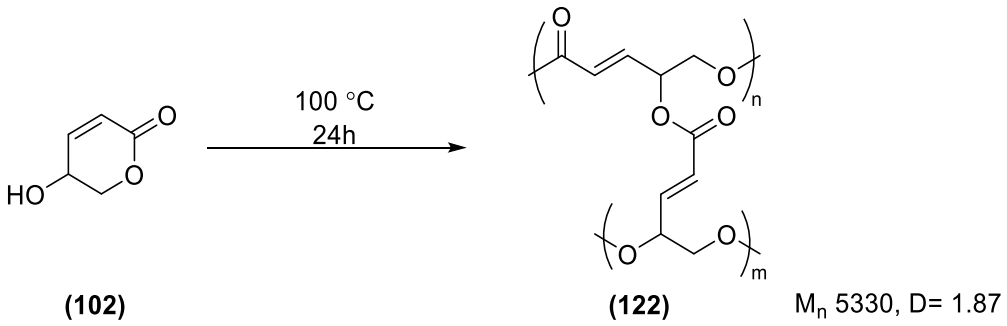


*Figure 4.5: The IR spectra of sm (starting material **(93)** and the resulting polymers entries 1, 3 and 5 of table 4.3*

The highest molecular weight was obtained from the mono-epoxide derivative of geraniol in THF at 60 °C for 120 hours and a relatively narrow dispersity of 1.22 Đ (Figure 4.4). The

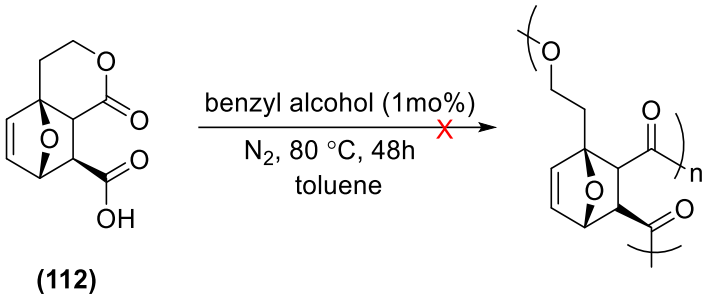
reactions were monitored by ^{1}H NMR, and the full conversion of the geraniol-epoxides derivatives was observed. The resulting polymers were precipitated in cold methanol to give a white solid material. The IR spectra of **120** showed the presence of the carbonyl of the ester of the formed oligomers around 1715 cm^{-1} (Figure 4.5). The epoxide groups of geraniol derivatives and the primary alcohol can open glutaric anhydride and propagate the polymerisation by $La(OTf)_3$. This will result in a tertiary alcohol in the resulting polymers which is unlikely to be involved in the polymerisation because of the steric hindrance.

Moreover, 5-hydroxy-5,6-dihydro-2H-pyran-2-one (**102**), which was prepared from furfural in chapter three, was also polymerised via ring-opening polymerisation of the lactone to produce a novel polyester. The reaction was carried out at 100 °C for 24 hours as a self-polymerisation to have a viscous material as an indication of a polymer. In this polymerisation, the hydroxyl group of the starting monomer acts as a nucleophile initiator, where the -OH of a monomer attacks the lactone of the other monomer and initiates the polymerisation. The reaction was monitored by ^{1}HNMR to show 47% conversion to polymer; a crude sample was also characterised by IR and GPC, confirming the presence of a polymer with molecular weight 5330 Da and 1.87 Đ and the monomer.



*Scheme 4.9: Self-polymerisation of **102** to afford a polyester.*

The IR showed a new carbonyl peak representing the carbonyl of the ester in the resulting polymer. This polyester has a double bond in the backbone of the polymer chain, which makes the polymer suitable for post-polymerisation modification such as dihydroxylation. Furthermore, the product of the Diels-Alder reaction in chapter three resulted in a unique monomer with four functional groups (alkene, lactone, and carboxylic) and two polymerisable groups (lactone and carboxylic). Hence, it can be used to produce novel polyesters via ring-opening polymerisation and polycondensation. Due to the time limitation, one attempt of polymerisation was carried out using benzyl alcohol as an initiator under nitrogen at 80 °C for 48 hours. Unfortunately, no conversion of the starting monomer was observed by the ^{1}HNMR.



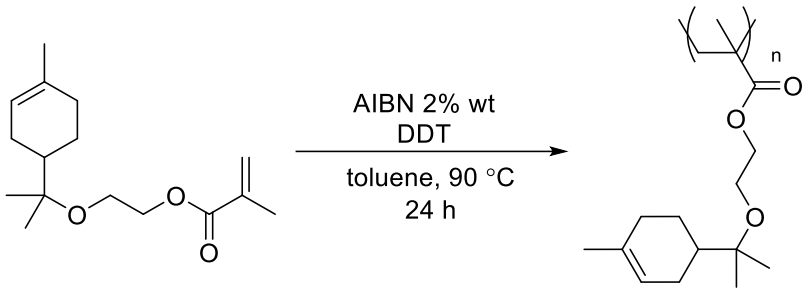
(112)

*Scheme 4.10: The polymerisation attempt of **112** and the structure of the potential polymer.*

4.6.3 Radical Polymerisation of α-pinene Derivatives:

Coupling ethylene glycol with α-pinene produced a novel chemical that has a hydroxyl group which can be functionalised (**71**). The reaction of methacryloyl chloride with this hydroxyl group introduced a double bond (**76**) that can be polymerised by radical polymerisation to produce polymethacrylate. The reaction was carried out using azobisisobutyronitrile (AIBN) as an initiator in toluene as a solvent at 90 °C (Scheme 4.11). Three reactions were carried out (Table 4.4). The first one was conducted without 1-dodecanethiol (DDT), and this resulted in a cross-linked insoluble polymer. When DDT (1%) was used to control the molecular weight

by chain transfer, a polymer of 5000 Da was produced after 96 hours but with a broad dispersity of 4.41 Đ. Increasing DDT to 3% resulted in a comparable molecular weight but with a narrower dispersity of 2.01 Đ.



(76) **(123)**

*Scheme 4.11: Polymerisation of methacrylate derivative of α-pinene (**76**) to produce a novel polymer*

*Table 3.4: Conditions and results of Polymerisation of methacrylate derivative of α-pinene (**76**).*

Entry	Monomer: Solvent (w:v)	DDT (w/w%)	M_n (g/mol)	Đ
1	1:2	-	-	-
2	1:2	1	5000	4.41
3	1:2	3	4000	2.01

1-Dodecanethiol is a thiol used to control the chain transfer. This is due to the weakness of the S–H bond and the high reactivity of thiyl radicals, which can significantly decrease the molecular weight of a polymer without significantly changing the polymerisation rate. The polymerisation was also monitored by ^{1}HNMR to show a full conversion.

4.7 Conclusion

In this chapter, ten novel monomers were used to produce novel polymers. Seven monomers (**77, 85, 86, 89, 93, 94, 102**) were successfully polymerised to afford novel polyesters with different molecular weights and dispersities. The highest obtained molecular weight was 8400

Da, and the lowest dispersity was 1.22 Đ. Furthermore, a novel polymethacrylate was obtained by a successful polymerisation of the α-pinene methacrylate monomer (**76**).

The polymerisation reactions can be optimised using different reaction conditions, catalyst type and quantity, solvent type and amount, temperature and pressure.

We attempted to test the thermal properties of the produced polymers, particularly the glass transition temperatures (Tg), using differential scanning calorimetry (DSC) in the range of –40 ℃ to 120 ℃. Unfortunately, no Tgs were found in this temperature range, so another attempt is recommended to be between -80 and 120 ℃. However, due to the time limitation we were not able to test them in that range.

Chapter Five:

5. Conclusion and Future Work:

5.1 Conclusion

Using biomass-derived compounds like terpenes and furfural to produce monomers and polymers for bioplastics is an emerging field in sustainable materials science. This approach offers a renewable alternative to conventional petroleum-based plastics, reducing environmental impact and promoting a circular economy.

In chapter two, several synthetic routes were explored to afford different monomer precursors and monomers with different polymerisable groups from biomass materials: α-pinene, limonene, β-pinene and geraniol.

The ethylene glycol addition to α-pinene gave a low yield, around 10% of the desired product (**71**), and a higher yield, around 35%, was obtained with 1-propanol **(72)** and 1-octanol **(73)**. The highest yield, 52% **(74)**, was obtained when Lewis acid catalysts were used. The alcohol derivative with methacrylate afforded 60% of the desired product **(76),** which can be used for radical polymerisation.

The cyclic-alkene group of α-pinene was utilised to open the ring and afford high monomers yields with diols (**77**, **78**). Furthermore, these diols were converted into the hydroxy-carboxy derivatives (**85**, **86**). Both diols and the hydroxy-carboxy derivatives can be utilised for polycondensation and produce novel polyesters.

The addition of alcohol to β-pinene produced a monomer (**88**) with two polymerisable groups: alcohol and olefin. This monomer was functionalised further to afford novel diols **(89**, **90)**

suitable for polycondensation, which produces novel polyesters. β-Pinene epoxide was also utilised for alkene and methacrylate additions **(91**, **92)**.

Geraniol was used to prepare novel epoxides, diols, and hydroxy-carboxy derivatives (**93**, **94**, **95**, **96,** and **98**) suitable for polycondensation and the synthesis of novel polyesters.

In chapter three, furfural, as a promising biomass platform, was utilised to manufacture products such as polymers and their monomers. Several chemical modifications were applied to furfural to obtain furfural dervatives with different functional groups; alcohol (**99**, **105**), lactone (**102**, **112**), epoxide (**104**), and carboxyl groups (**112**).

The Achmatowicz rearrangement (AchR) was used as an oxidative ring-expansion rearrangement of functionalised furfuryl alcohols to densely functionalised dihydropyranone acetal (**100**), which converted to the lactone derivative (**102**). This lactone can be used to produce functinalisable novel polyester via ring-opening polymerisation. The alkene group of the backbone of the potential polyester can be utilised by post-polymerisation modifications.

AchR with 2-(furan-2-yl)ethanol (**105**) to afford the potential seven-membered ring (**106**) was not successful. The reaction yielded another thermodynamically stable product (**109**).

A novel bicyclic product (**112**) was made via the Diels–Alder reaction utilising furfural and maleic anhydride. This potential monomer has four functional groups (alkene, lactone, and carboxylic) and two polymerisable groups (lactone and carboxylic). Hence, it can be used to produce novel polyesters via ring-opening polymerisation and polycondensation. The alkene and epoxide groups can also be modified pre- and post-polymerisation.

In chapter four, ten novel monomers were used to produce novel polymers. Seven monomers (**77, 85, 86, 89, 93, 94, 102**) were successfully polymerised to afford novel polyesters with

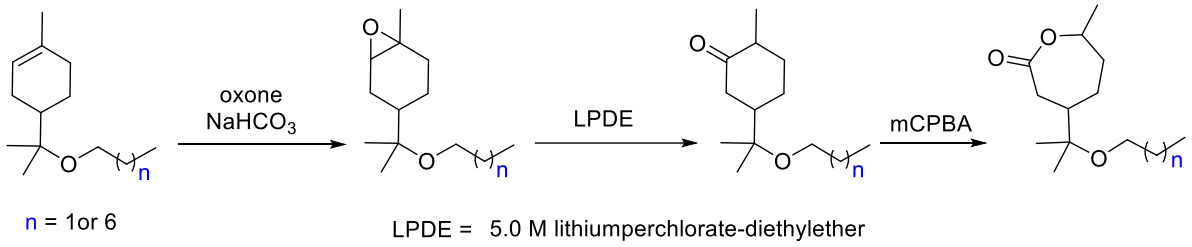
different molecular weights and dispersities. The highest obtained molecular weight was 8400 Da, and the lowest dispersity was 1.22 Đ. Furthermore, a novel polymethacrylate was obtained by a successful polymerisation of the α-pinene methacrylate monomer (**76**).

The polymerisation reactions can be optimised using different reaction conditions, catalyst type and quantity, solvent type and amount, temperature and pressure.

5.2 Future Work:

Using the bioeconomy-centred circular economy model will lessen the reliance on fossil fuels. Biorefineries will continue to transform biomass into bioenergy and create valuable products, including molecules that can serve as the basis for producing biopolymers and bioplastics. Terpenes, furfural, and all other biomass chemicals can be used to produce several chemical modifications and green synthetic routes.

In this work, we prepared α-pinene derivatives of **74** and **75**, which can be utilised to a 7-membered ring of lactone via this suggested synthetic route (Scheme 5.1)



Scheme 5.1: A proposed synthetic route to prepare a 7-member ring of lactone from α-pinene derivatives.

First, a stereoselective epoxidation can be obtained by following the protocol of Wong et, al.[136] The selection of the solvents needs to be optimised to maximise the solubility of the reagents and the, in turn, maximise the yield. Then, chemo- and regioselective conversion of the produced epoxides to carbonyl can be carried out by following the method of Ramasamy et al.

using lithium perchlorate-diethyl ether (LDPE) medium.[137] Finally, the ring expansion from the ketone derivative to a 7-member ring of lactone can be achieved via Corma et al. 's methodology.[138]

This potential monomer can be polymerised by ROP to afford a novel polyester.

Chapter Six:

6. Experimental

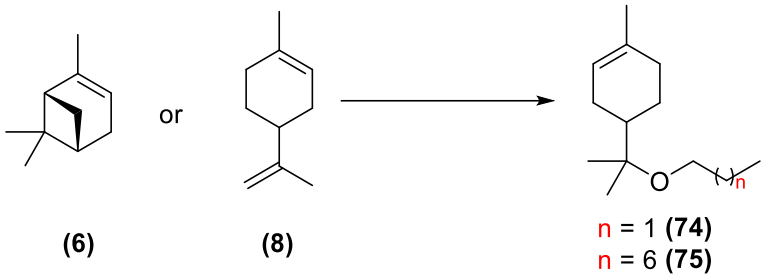
6.1 General Experimental

All solvents and reagents were purchased from commercial suppliers and used directly without further purification. All water was deionised before use, and experiments were carried out under an inert atmosphere of nitrogen. Cooling to 0 °C was affected using an ice-water bath. Cooling to -78 °C using dry ice and acetone. THF was used from the solvent tower. All solutions are saturated unless stated otherwise. TLCs were performed on either silica gel on aluminium or on aluminium oxide on PET foil. They were visualised using a potassium permanganate stain, phosphomolybdic acid, or vanillin dip. ^{1}H and ^{13}C NMR spectra were recorded in *$CDCl_3$*, *DMSO-d_6* at ambient temperature using Bruker DPX400 (400 MHz), AV400 (400 MHz), AV3400HD (400 MHz), AV3400 (400 MHz). Data are expressed as chemical shifts in parts per million (ppm). ^{1}H NMR chemical shifts (δ) were reported in ppm relative to the ^{1}H signals in the solvent - *$CDCl_3$*: δ 7.26 ppm, *DMSO-d_6*: δ 2.50 ppm. ^{13}C NMR was recorded on a 75 MHz spectrometer and chemical shifts (δ) were reported in ppm relative to the ^{13}C signals in the solvent - *$CDCl_3$*: 77.16 ppm, DMSO-*d_6*: δ 39.51 ppm. Couplings (*J*) are given in Hertz (Hz), and abbreviations for NMR multiplet analysis were used as follows: s = singlet, d = doublet, t = triplet, q = quartet, qu = quintet, sep = septet, br = broad, app = apparent, m = multiplet. Infra-red spectra were recorded using a Bruker Tensor 27 FT-IR spectrophotometer using either an ATR attachment or a solution cell using $CHCl_3$ as the solvent and their peaks are quoted as υ_{max} in cm^{-1}. High-resolution mass spectra were obtained using a Bruker MicroTOF mass spectrometer operating in electrospray ionisation (ESI) mode.

Gel permeation chromatography (GPC), an Agilent 1260 Infinity Series HPLC (Agilent Technologies, USA), at room temperature using two Agilent PLgel 5 μm mixed-C columns (300 x 7.5 mm) in series with a PL-gel 10 μm Guard Column (50 x 7.5 mm) fitted with a differential refractive index detector (DRI) was used. THF (HPLC grade, Fisher Scientific) was used as the eluent at room temperature with two Agilent PL-gel mixed-E columns in series at a flow rate of 1 mL min^{-1}. Poly(methyl methacrylate) standards were used as a calibration curve with ASTRA software (Wyatt Technology, USA). This was used to determine the M_n, M_w and molecular weight distribution and dispersity (Đ, M_w/M_n).

6.2 Synthesis of Chapter Two

α-Terpenyl derivatives:

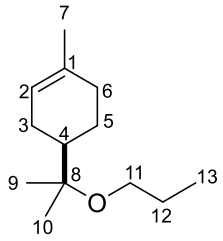


Synthesis of 1-methyl-4-(2-propoxypropan-2-yl)cyclohex-1-ene (74):

Method 1: To a stirred solution of (-)-α-pinene **(6)** (19.9 g, 146.4 mmol) and 1-propanol **(72)** (8.0 g, 133.1 mmol) in dry dichloromethane (250 mL) was added anhydrous $FeCl_3$ (4.3 g, 26.6 mmol) at 0 °C. The resulting mixture was stirred at room temperature for 1.3 h. After complete conversion as indicated by TLC, the reaction mixture was quenched with water (2×200 mL) and extracted with dichloromethane (3 × 100 mL). The combined organic layers were dried over $MgSO_4$ and concentrated in vacuo. The resulting product was purified by a short layer of silica gel column chromatography using petroleum ether as an eluent to afford pure (**74**) (13.5 g, 52%).

Method 2: To a mixture of (-)-α-pinene **(6)** (19.0 g, 139.8 mmol) and 1-propanol **(72)** (7.0 g, 116.5 mmol) was added triflic acid (0.52 mL, 5.83 mmol) as dropwise, the reaction was stirred at room temperature for 72 hours, the reaction mixture was quenched with water (2×200 mL) and extracted with EtOAc (3 × 300 mL), The combined organic layers and washed with brine (1×200 mL), then were dried over $MgSO_4$ and concentrated in vacuo. The resulting product

was purified by flash column chromatography with petroleum ether/diethyl ether 9:1 to afford pure (**74**) (8.0 g, 35%).



(74)

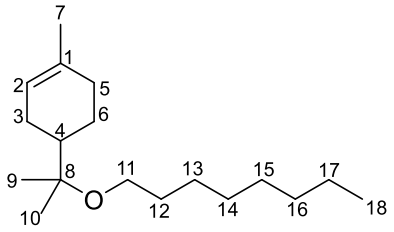
As a yellow oil. $\mathbf{R}_f$(petroleum ether: diethylether 9:1): 0.29; **IR** (KBr) ν_{max}/cm^{-1}: 2958, 2927, 2872, 1706,1455, 1377, 1077, 1007; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.40 (1H, dd, H-2, *J* = 7.5, 5.1), 3.28 (t, *J* = 7.5 Hz, 2H, H-11), 2.04 -1.80 (m, 6H, H-3, H-4, H-5, H-6), 1.66 (3H, s, H-7), 1.55-1.51 (m, 2H, H-12), 1.31-1.28 (m, 1H, H′-5), 1.12 (s, 3H, H-9), 1.10 (s, 3H, H-10), 0.92 (t, *J* = 7.4 Hz, 3H, H-13); **^{13}C NMR** (101 MHz, CDCl3) δ 133.8 (C-1), 121.1 (C-2), 75.9 (C-8), 62.3 (C-11), 42.1 (C-4), 31.1 (C-6), 26.9 (C-3), 24.0 (C-5), 23.9 (C-12), 23.3 (C-7), 22.9 (C-9), 22.6 (C-10), 10.8 (C-13); **HRMS** (ESI, $[C_{13}H_{24}O+H]^+$): measured 197.1897, theoretical 197.1900.

Synthesis of 1-methyl-4-(2-(octyloxy)propan-2-yl)cyclohex-1-ene **(75)**

Method 1: To a stirred solution of (-)-α-pinene **(6)** (9.50 g, 69.6 mmol) and 1-octanol **(73)** (8.24 g, 63.30 mmol) in dichloromethane (250 mL) was added anhydrous $FeCl_3$ (2.10 g, 12.7 mmol) at 0 °C. The resulting mixture was stirred at room temperature for 2 h. After complete conversion as indicated by TLC, the reaction mixture was quenched with water (100 mL) and extracted with dichloromethane (3 × 100 mL). The combined organic layers were dried over anhydrous $MgSO_4$ and concentrated in vacuo. The resulting product was purified by a short

layer of silica gel column chromatography using petroleum ether as an eluent to afford pure (**75**) (8.2 g, 49%).

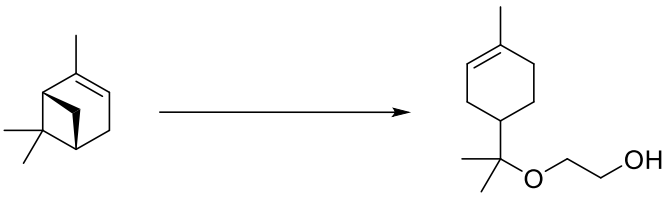
Method 2: To a mixture of (-)-α-pinene **(6)** (7.54 g, 55.29 mmol) and 1-octanol **(73)** (6.0 g, 46.07 mmol) was added triflic acid (0.041 mL, 0.46 mmol) as dropwise, the reaction was stirred at room temperature for 72 hours, the reaction mixture was quenched with water (2×100 mL) and extracted with EtOAc (3 × 200 mL), The combined organic layers and washed with brine (1×200 mL), then were dried over anhydrous $MgSO_4$ and concentrated in vacuo. The resulting product was purified by flash column chromatography with petroleum ether/diethyl ether 9:1 to afford pure (**75**) (3.8 g, 31%).



(75)

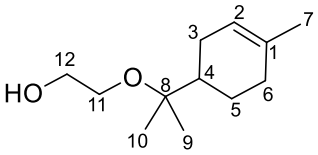
As a yellow oil. $\mathbf{R}_f$(petroleum ether: diethylether 9:1): 0.28; **IR** (KBr) ν_{max}/cm^{-1} : 2957, 2924, 2855, 1750, 1454,1362, 1077, 916; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.40 (brs,1H, H-2) , 3.28 (t, *J* = 6.7 Hz, 2H, H-11), 2.03-1.70 (m, 6H, H-3, H-4, H-5, H-6), 1.66 (s, 3H, H-7), 1.56-1.51 (m, 2H, H-12) , 1.32-1.23 (m, 11H, H-5,13,14,15,16 and 17), 1.08 (s, 3H, H-9), 1.07 (s, 3H, H-10), 0.92 (t, *J* = 3.6 Hz, 3H, H-18); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 133.5 (C-1), 121.0 (C-2), 75.6 (C-8), 60.5 (C-11), 42.1 (C-4), 31.9 (C-12) , 31.1 (C-6), 30.7 (C-13), 29.5 (C-14), 29.4 (C-15), 26.8 (C-16), 26.4 (C-3), 23.9 (C-5), 23.3 (C-7), 22.8 (C-9), 22.7 (C-10), 22.4 (C-17), 14.0 (C-18); **HRMS** (ESI, $[C_{18}H_{34}O+H]^+$): measured 267.2680, theoretical 267.2682.

Synthesis of 2-((2-(4-methylcyclohex-3-en-1-yl)propan-2-yl)oxy)ethan-1-ol **(71)**



(6) **(71)**

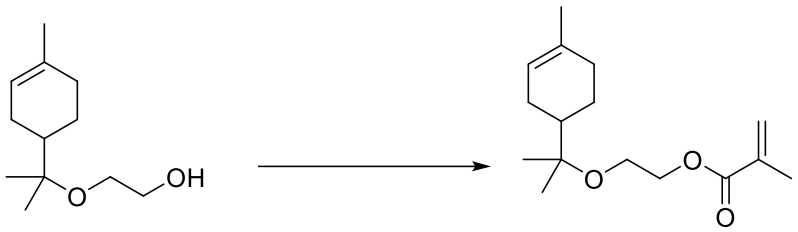
A mixture of (-)-α-pinene **(6)** (10 g, 73.4 mmol), ethylene glycol **(41)** (9.1 g, 146.8 mmol) and *p*-toluenesulfonic acid monohydrate (0.67 g, 3.52 mmol) was stirred at room temperature for 72 hours. The reaction mixture was diluted using water (30 mL), and the product was extracted using EtOAc (3 x 30 mL). The organic layers were combined and washed with brine (20 mL), dried over MgSO4 and the solvent was removed in vacuo. The crude product was purified using silica gel chromatography (pentane/EtOAc 7:3) to afford the title compound (3.6 g, 25%).



(71)

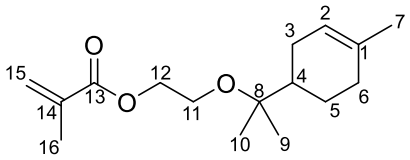
As a pale yellow oil; $\mathbf{R_f}$ (pentane/EtOAc 7:3) 0.60; **IR** (KBr) ν_{max}/cm^{-1} 3412, 2963, 2922, 2872, 1740, 1706, 1438, 1379, 1363, 1300, 1247, 1223, 1177, 1158, 1138, 1118, 1051, 996, 952, 917, 891, 770, 636; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.36 (s, 1H, H-2), 3.66 (q, *J* = 4.3 Hz, 2H, H-12), 3.42 (dd, *J* = 5.2, 4.2 Hz, 2H, H-11), 2.42 (brs, 1H, OH), 2.03 – 1.83 (m, 3H, H-3 and H-4), 1.83 – 1.67 (m, 2H, H-6), 1.63 (s, 3H, H-7), 1.33 – 1.15 (m, 2H, H-5), 1.11 (s, 3H, H-9), 1.110 (s, 3H, H-10); **^{13}C NMR** (101 MHz, CDCl3) δ 133.9 (C-1), 120.7 (C-2), 76.8 (C-8), 62.3 (C-11), 61.8 (C-12), 42.1 (C-4), 31.0 (C-6), 26.8 (C-3), 23.9 (C-10), 23.3 (C-9), 22.9 (C-5), 22.5 (C-7); **HRMS** (ESI, $[C_{12}H_{22}O_2+Na]^+$): measured 221.1504, theoretical 221.1512.

Synthesis of 2-((2-(4-methylcyclohex-3-en-1-yl)propan-2-yl)oxy)ethyl methacrylate **(76)**



(71) **(76)**

To a cold solution (0 °C) of 2-((2-(4-methylcyclohex-3-en-1-yl)propan-2-yl)oxy)ethan-1-ol (1.5 g, 7.56 mmol) in DCM (60 mL) was added sequentially Et_3N (2.0 mL, 14.36 mmol) and methacryloyl chloride (1.11 mL, 11.34 mmol) and the mixture was stirred during 24 h warming to room temperature. After the reaction was complete the reaction was quenched by addition of saturated aqueous solution of $NaHCO_3$(1x15 mL). Aqueous phase was extracted with DCM (3x30 mL). Combined organic layers were washed with brine (1x20 mL), dried with MgSO4 and solvent was evaporated. The crude product was purified using silica gel chromatography (pentene/EtOAc 9:1) to afford the title compound (1.2 g, 60%).

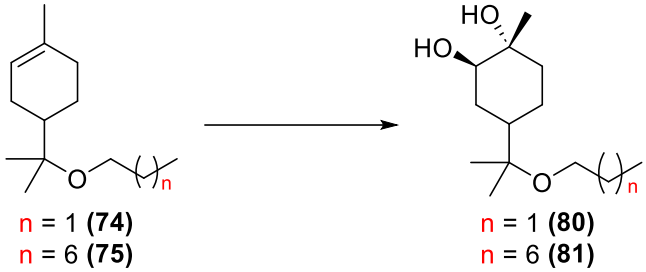


(76)

As a colorless oil; $\mathbf{R_f}$ (pentene/EtOAc 9:1) 0.71; **IR** (KBr) ν_{max}/cm^{-1} 2983, 1737, 1638, 1372, 1235, 1169, 1096, 1044, 939, 847; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 6.14 – 6.05 (m, 1H, H-15), 5.57 – 5.49 (m, 1H, H´-15), 5.35 (s, 1H, H-2), 4.24 – 4.18 (m, 2H, H-12), 3.58 – 3.53 (m, 2H, H-11), 2.03 – 1.97 (m, 2H, H-3), 1.93 (*J* = 1.8 Hz, 3H, H-16), 1.87 – 1.69 (m, 2H, H-6), 1.62 (s, 3H, H-7), 1.31 – 1.18 (m, 3H, H-4 and H-5), 1.09 (s, 3H, H-9), 1.08 (s, 3H, H-10); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 167.3 (C-13), 136.3 (C-14), 133.9 (C-1), 125.4 (C-15), 120.8 (C-2), 76.9 (C-8), 64.5 (C-11), 59.0 (C-12), 41.9 (C-4), 31.0 (C-6), 26.7 (C-3), 23.8 (C-10), 23.3

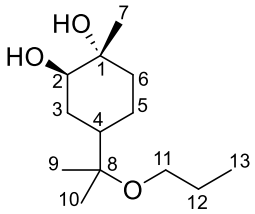
(C-9), 22.8 (C-5), 22.4 (C-7), 18.3 (C-16); **HRMS** (ESI, $[C_{16}H_{26}O_3+Na]^+$): measured 289.1775, theoretical 289.1774.

Diols of α-terpenyl derivatives:



Synthesis of 1-methyl-4-(2-propoxypropan-2-yl)cyclohexane-1,2-diol **(80)**

To a round-bottom flask was added alkene **(74)** substrate (7.0 g, 35.65 mmol) to CH_3CN (250 mL) and H_2O (190 mL). Then were added a mixture of Oxone (32.34 g, 106.95 mmol) and $NaHCO_3$ (7.49 g, 89.13 mmol) and vigorously stirred at ambient temperature for 72 hours at room temperature. The mixture was filtered and extracted with diethyl ether (3 × 200 mL). The combined organic layers were washed with brine, dried over $MgSO_4$, filtered, and concentrated under reduced pressure to afford the title compound (7.14 g, 87 %).



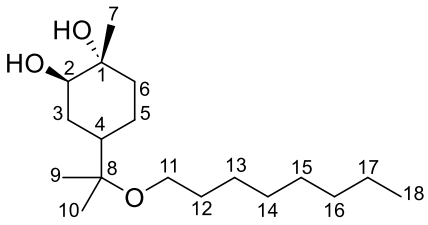
(80)

As a colorless oil. $\mathbf{R_f}$(pentane:EtOAc 1;1): 0.41; **IR** (KBr, cm^{-1}) $\mathbf{V_{max}}$ 3389, 2961, 2936, 2875, 1461, 1230, 1128, 1056, 1037, 999, 909; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 3.63 (m, 1H, H-2), 3.28 (td, *J* = 6.7, 1.9 Hz, 2H, H-11), 1.81-1.68 (m, 4H, H-5, H-3), 1.59-148 (m, 5H, H-6, H-4 and H-12), 1.26 (s, 3H, H-7), 1.12 (s, 3H, H-10), 1.10 (s, 3H, H-9), 0.91 (t, *J* = 7.4 Hz, 3H, H-

13); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 76.1 (C-8), 74.1 (C-2), 71.1 (C-1), 62.3 (C-11), 38.3 (C-4), 33.7 (C-6), 29.9 (C-3), 27.5 (C-10), 23.8 (C-9), 23.1 (C-7), 22.5 (C-12), 22.0 (C-5), 10.8 (C-13); **HRMS** (ESI, $[C_{13}H_{26}O_3+Na]^+$): measured 251.1613, theoretical 251.1618.

Synthesis of 1-methyl-4-(2-(octyloxy)propan-2-yl)cyclohexane-1,2-diol **(81)**

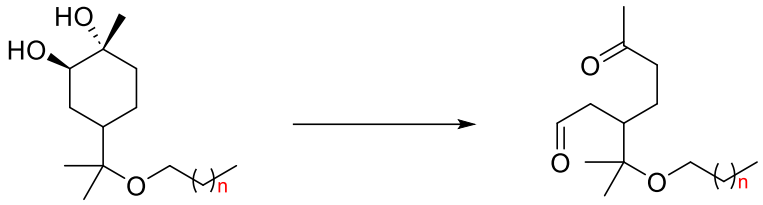
To a round-bottom flask was added alkene **(75)** substrate (5.0 g, 18.76 mmol) to CH_3CN (150 mL) and H_2O (115 mL). Then were added a mixture of Oxone (18.45 g, 16.5 mmol) and $NaHCO_3$ (3.94 g, 46.9 mmol) and vigorously stirred at ambient temperature for 120 hours at room temperature. The mixture was filtered and extracted with diethyl ether (3 × 200 mL). The combined organic layers were washed with brine, dried over $MgSO_4$, filtered, and concentrated under reduced pressure to afford the title compound (4.72 g, 84%).



(81)

As a colourless oil. **R_f**(pentane:EtOAc 1;1) 0.19; **IR** (KBr, cm^{-1}) **V_{max}** 3407, 2924, 2855, 1459, 1363, 1036; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 3.54 (t, *J* = 3.3 Hz, 1H, H-2), 3.27 – 3.17 (m, 2H, H-11), 1.84 – 1.51 (m, 4H, H-3 and H-5), 1.48 – 1.35 (m, 3H, H-6 and H-4), 1.23 – 1.17 (m, 12H, H-12, H-13, H-14, H-15, H-16 and H-17), 1.16 (s, 3H, H-7), 1.06 – 1.01 (m, 6H, H-9 and H-10), 0.81 (t, *J* = 6.8 Hz, 3H, H-18); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 76.1 (C-8), 74.1 (C-2), 71.0 (C-1), 60.7 (C-11), 38.2 (C-4) , 33.7 (C-6), 31.9 (C-3), 30.8 (C-16), 29.9 (C-13), 29.5 (C-10), 29.3 (C-9), 27.5 (C-12), 26.3 (C-14), 23.1 (C-15), 22.7 (C-7), 22.5 (C-17), 22.0 (C-5), 14.1 (C-18); **HRMS** (ESI, $[C_{18}H_{36}O_3+H]^+$): measured 301.2747, theoretical 301.2737.

Oxidative cleavage of diol α-terpenyl derivatives

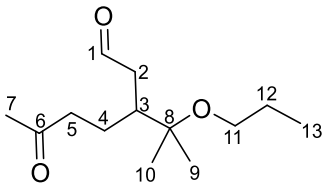


n = 1 **(80)**
n = 6 **(81)**

n = 1 **(82)**
n = 6 **(79)**

Synthesis of 6-oxo-3-(2-propoxypropan-2-yl)heptanal **(82)**

To a stirred of 1-methyl-4-(2-propoxypropan-2-yl)cyclohexane-1,2-diol **(80)** (1.5 g, 6.51mmol) in acetonitrile (50 mL) and water (38 mL) was added $NaIO_4$ (2.10 g, 9.77 mmol) at room temperature. The reaction was monitored by TLC. After completion in 48 h, the reaction was extraction with diethyl ether, and the two layers were separated. The aqueous layer was extracted with diethyl ether three times. The combined organic layer was washed with brine, dried over $MgSO_4$, filtered, and concentrated to afford the title compound (1.25 g, 84% yield).



(82)

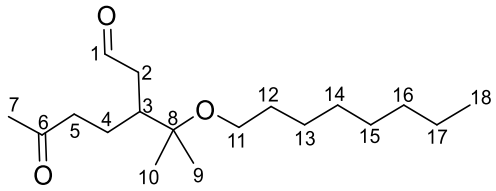
As light yellow oil, $\mathbf{R}_f$(pentane:EtOAc 7;3) 0.8 ; **IR** (KBr, cm^{-1}) $\mathbf{V}_{max}$ 2962, 2935, 2875, 1715, 1456, 1414, 1365, 1226, 1167, 1144, 1111, 1075, 1034, 1005, 876, 549; ; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 9.66 (dd, *J* = 3.0, 1.6 Hz, 1H, H-1), 3.21 (t, *J* = 7.5 Hz, 2H, H-11), 2.64 – 2.32 (m, 4H, H-5 and H-2), 2.12 (s, 3H, H-7), 1.87– 1.75 (m, 1H, H-3), 1.49-1.38 (m, 2H, H-4), 1.35 – 1.20 (m, 2H, H-12), 1.17 (s, 3H, H-10), 1.03 (3H, s, H-9), 0.84 (t, *J* = 7.4 Hz, 3H, H-13); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 208.3 (C-6), 202.1 (C-1), 76.5 (C-8), 61.8 (C-11), 44.6 (C-5), 42.8

(C-3), 42.2 (C-2), 31.8 (C-7), 23.6 (C-10), 23.5 (C-9), 22.6 (C-12), 20.4 (C-4), 10.7 (C-13); **HRMS** (ESI, $[C_{13}H_{24}O_3+Na]^+$): measured 251.1619, theoretical 251.1618.

Synthesis of 3-(2-(octyloxy)propan-2-yl)-6-oxoheptanal **(79)**

Method 1: To a stirred solution of 1-methyl-4-(2-(octyloxy)propan-2-yl)cyclohexane-1,2-diol **(81)** (1.5 g, 4.99 mmol) in acetonitrile (60 mL) and distilled water (45 mL) was added $NaIO_4$ (1.6 g, 7.49 mmol) at room temperature. The reaction was monitored by TLC. After completion in 72h, the reaction was extracted with diethyl ether, and the two layers were separated. The aqueous layer was extracted with diethyl ether three times. The combined organic layer was washed with brine, dried over $MgSO_4$, filtered, and concentrated to afford the title compound (1.20 g, 81% yield).

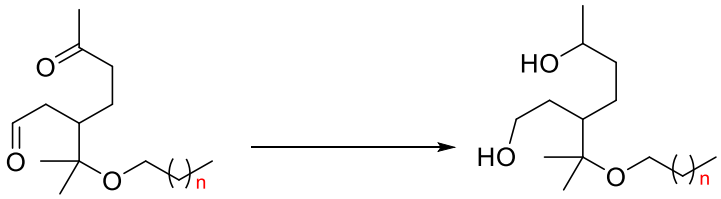
Method 2: To a stirred mixture of **75** (2 g, 7.51 mmol) and $RuCl_3$ solution (10 mL, 0.26 mmol, 3.5 mol %) in DCM (50 mL) and distilled water (40 mL) was added in portions $NaIO_4$ (6.43 g, 30.04 mmol) for 10 min at room temperature. The reaction was monitored by TLC. After completion, in 48 h, the reaction was quenched with a saturated aqueous solution of $Na_2S_2O_3$, and the two layers were separated. The aqueous layer was extracted with EtOAc three times. The combined organic layer was washed with water and brine, dried over $MgSO_4$, filtered, and concentrated to afford (0.88 g, 39% yield).



(79)

As light yellow oil, **R_f**(pentane:EtOAc 7;3) 0.75; **IR** (KBr, cm^{-1}) **V_{max}** 2966, 2925, 2855, 1715, 1365, 1224, 1166, 1144, 1073, 723; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 9.69 (dd, *J* = 3.0, 1.6 Hz, 1H, H-1), 3.26 (td, *J* = 6.6, 1.4 Hz, 2H, H-11), 2.60 – 2.41 (m, 4H, H-5 and H-2), 2.15 (s, 3H, H-7), 1.88 – 1.78 (m, 2H, H-4), 1.47 – 1.41 (m, 3H, H-3 and 12), 1.30 – 1.26 (m, 10H, H-13, 14, 15, 16 and17), 1.19 (s, 3H, H-9), 1.05 (s, 3H, H-10), 0.88 (t, *J* = 6.7 Hz, 3H, H-18); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 208.4 (C-6), 202.1 (C-1), 76.5 (C-8), 60.8 (C-11), 44.6 (C-5), 42.8 (C-3), 42.2 (C-2), 31.8 (C-12), 30.2 (C-7), 29.9 (C-14), 29.4 (C-15), 29.2 (C-13), 26.2 (C-16) , 24.5 (C-10), 23.6 (C-9), 22.6 (C-17), 20.4 (C-4), 14.0 (C-18); **HRMS** (ESI, $[C_{18}H_{34}O_3+Na]^+$): measured 312.2410, theoretical 321.2400.

Reduction of Aldehyde-ketone to diols:

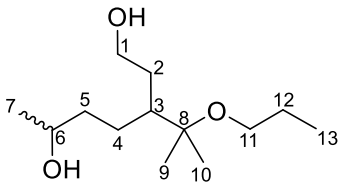


n = 1 **(82)**
n = 6 **(79)**

n = 1 **(77)**
n = 6 **(78)**

Synthesis of 3-(2-propoxypropan-2-yl)heptane-1,6-diol **(77)**

To a solution of 6-oxo-3-(2-propoxypropan-2-yl)heptanal **(82)** (1.6 g, 7.01 mmol) in methanol (30 mL) cooled at 0 °C, sodium borohydride (0.58 g, 15.42 mmol) was added portion-wise and the resulting mixture was stirred for 4 h at room temperature. Product formation was checked by TLC. The reaction was quenched by adding (30 mL) of water and extracted with ethyl acetate (3 × 100 mL). The collected organic layer was dried over $MgSO_4$ and concentrated to afford the title compound as a mixture of diastereoisomers (1.5 g, 92%).

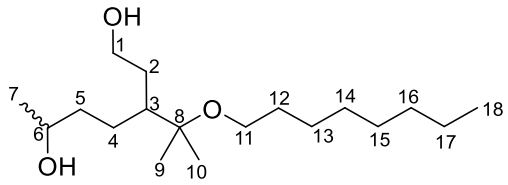


(77)

As light yellow oil; $\mathbf{R_f}$(pentane:EtOAc 7;3) 0.46, 0.54; **IR** (KBr, cm^{-1}) $\mathbf{V_{max}}$ 3357, 2961, 2933, 2874, 1459, 1366, 1148, 1111, 1073, 1007, 947, 844; **^{1}H NMR** 1H NMR (400 MHz, $CDCl_3$) δ 3.83 – 3.64 (m, 2H, H-1), 3.62 – 3.47 (m, 1H, H-6), 3.31 (tdd, J = 6.7, 5.1, 1.7 Hz, 2H, H-11), 1.88-1.71 (m, 1H, H-3), 1.69 – 1.44 (m, 8H, H-2, H-4, H-5, H-12), 1.16 (s, 3H, H-9), 1.10 (s, 3H, H-10), 1.09 (s, 3H, H-7), 0.86 (t, *J* = 7.4 Hz, 3H, H-13); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 77.7, 77.6 (C-8), 68.4, 67.6 (C-6), 62.8, 62.8 (C-11), 62.1, 62.0 (C-1), 46.3, 46.0 (C-3), 38.3, 38.1 (C-2), 33.3, 33.2 (C-5), 27.4, 27.2 (C-4), 23.6, 23.5 (C-7), 23.5, 23.4 (C-12), 23.2, 21.1 (C-4), 10.7, 10.7 (C-13); **HRMS** (ESI, $[C_{13}H_{28}O_3+H]^+$): measured 233.2124, theoretical 233.2111.

Synthesis of 3-(2-(octyloxy)propan-2-yl)heptane-1,6-diol **(78)**

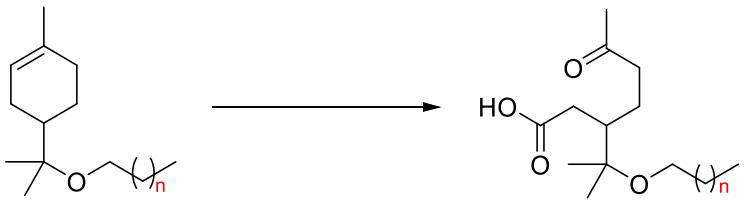
To a solution of 3-(2-(octyloxy)propan-2-yl)-6-oxoheptanal **(79)** (1.22 g, 4.09 mmol) in methanol (40 mL) cooled at 0 °C. Sodium borohydride (0.34 g, mmol) was added portion-wise to the resulting mixture and stirred for 5 h at room temperature. Product formation was checked by TLC. The reaction was quenched by adding (40 mL) of water and extracted with ethyl acetate (3 × 100). The combined organic layer was dried over $MgSO_4$ and concentrated to afford the title compound as a mixture of diastereoisomers (1.12 g, 91%).



(78)

As light yellow oil; $\mathbf{R_f}$ (pentane:EtOAc 7;3) 0.26, 0.37 ; **IR** (KBr, cm^{-1}) 3351, 2955, 2924, 2855, 1743, 1727, 1459, 1372, 1239, 1176, 1148, 1049, 946, 914, 607; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 3.84 – 3.63 (m, 2H, H-1), 3.58 – 3.46 (m, 1H, H-6), 3.38 – 3.28 (m, 2H, H-11), 1.85 – 1.68 (m, 1H, H-3), 1.63 – 1.39 (m, 8H, H-2, H-4, H-5 and H-12), 1.28 – 1.22 (m, 10H, H-13, H-14, H-15, H-16 and H-17), 1.20 – 1.12 (m, 6H, H-9 and H-10), 1.10 – 1.06 (m, 3H, H-7), 0.86 (t, J = 6.7 Hz,3H, H-18). **^{13}C NMR** (101 MHz, CDCl3) δ 77.7, 77.6 (C-8), 68.3, 67.7 (C-6), 62.0, 61.9 (C-11), 61.2, 61.1 (C-1), 46.2, 45.9 (C-3), 38.2, 38.1 (C-5), 33.3, 33.2 (C-16), 31.8 (C-12), 30.3 (C-14), 29.4 (C-15), 29.3 (C-13), 27.4, 27.2 (2), 26.2, 26.1 (C-9), 23.4 (C-10), 23.5, 23.2 (C-7), 22.6 (C-17), 21.1 (C-4), 14.1 (C-18); **HRMS** (ESI, $[C_{18}H_{38}O_3+H]^+$): measured 303.2899, theoretical 303.2894.

Oxidative cleavage of α-terpenyl derivatives:



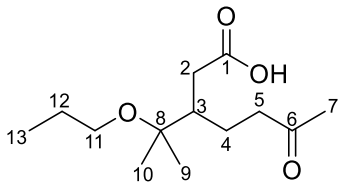
n = 1 **(74)**
n = 6 **(75)**

n = 1 **(83)**
n = 6 **(84)**

Synthesis of 6-oxo-3-(2-propoxypropan-2-yl)heptanoic acid **(83)**

Alkene **(74)** substrate (2 g, 10.19 mmol), Oxone (12.5 g, 40.76 mmol) and sodium periodate (6.5 g, 30.57 mmol) were added to a mixture of MeCN (45 mL) and H_2O (45 mL) and

vigorously stirred at ambient temperature for 120 hours. Subsequently, the mixture was filtered and extracted with diethyl ether (3 × 80 mL). The combined organic layers were washed with brine and dried over $MgSO_4$. The solvent was removed under reduced pressure to afford the title compound (1.9 g, 76 %).



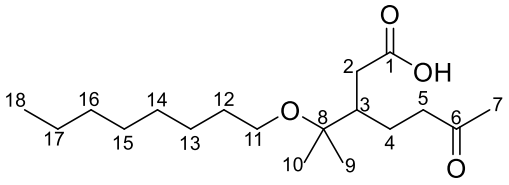
(83)

As a yellow oil. $\mathbf{R_f}$(hexene:EtOAc 7:3): 0.47; **IR** (KBr, cm^{-1}) $\mathbf{V_{max}}$: 3290, 2967, 2910, 2860, 2830, 1728, 1689, 1380, 1279, 1143, 1071; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 10.28 (brs, 1H, H-1) 3.22 (t, *J* = 6.6 Hz, 2H, H-11), 2.55 (dd, *J* = 16.1, 5.0 Hz, 1H, H-5), 2.48 – 2.40 (m, 2H, H-2 and H′-5), 2.05 (s, 3H, H-7), 2.04 – 1.95 (m, 2H, H′-2 and H-3), 1.79 – 1.72 (m 1H, H-12), 1.42 (q, *J* = 7.0 Hz, 2H, H-4), 1.32 – 1.21 (m, 1H, H-12), 1.12 (s, 3H, 9), 1.01 (s, 3H, H-10), 0.80 (t, *J* = 7.4 Hz, 3H, H-13); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 208.6 (C-6), 178.3 (C-1), 77.1 (C-8), 62.5 (C-11), 43.1 (C-3), 41.9 (C-5), 34.9 (C-2), 29.8 (C-7), 24.8 (C-10), 23.4 (C-9), 23.3(C-12), 21.3 (C-4), 10.6 (C-13); **HRMS** (ESI, $[C_{13}H_{24}O_4+Na]^+$): measured 267.1575, theoretical 267.1567.

Synthesis of 3-(2-(octyloxy)propan-2-yl)-6-oxoheptanoic acid **(84)**

Alkene **(75)** substrate (2 g, 7.51 mmol), Oxone (18.5 g, 60.08 mmol), and sodium periodate (9.65 g, 45.06 mmol) were added to a mixture of MeCN (80 mL) and H_2O (80 mL) and vigorously stirred at ambient temperature for 216 hours. Subsequently, the mixture was filtered and extracted with diethyl ether (3 × 100 mL). Subsequently, the combined organic layers were

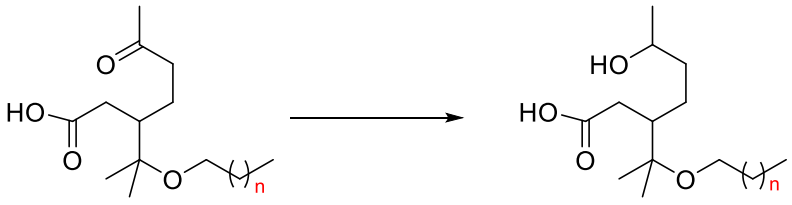
washed with brine and dried over $MgSO_4$. The solvent was removed under reduced pressure to afford the title compound (1.75 g, 74%).



(84)

As a yellow oil. $\mathbf{R_f}$(hexene:EtOAc 7:3): 0.47; **IR** (KBr, cm^{-1}) $\mathbf{V_{max}}$ 3429, 2960, 2934, 2875, 1766, 1724, 1461, 1375, 1375, 1242, 1174, 1130, 1073, 1035; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 3.30 (t, *J* = 6.7 Hz, 2H, H-11), 2.61 (dd, *J* = 16.1, 4.9 Hz, 1H, H-5), 2.55 – 2.42 (m, 2H, H′-5 and H-2), 2.11 (s, 3H, H-7), 2.07 – 1.92 (m, 3H, H′-2 and H-12), 1.47-1.41 (m, 3H, H-3 and H-4), 1.24 (m, 10H, H-13- H-14, H-15, H-16 and H-17), 1.17 (s, 3H, H-10), 1.06 (s, 3H, H-9), 0.84 (t, *J* = 6.7 Hz, 3H, H-18); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 208.9 (C-6), 178.4 (C-1), 76.9 (C-8), 61.1 (C-11), 43.3 (C-5), 42.1 (C-2), 35.2 (C-3), 31.8 (C-12), 30.2 (C-13), 29.9 (C-16), 29.4 (C-7), 29.2 (C-14), 26.2 (C-15), 24.8 (C-9), 23.4 (C-10), 22.6 (C-17), 21.4 (C-4), 14.1 (C-18); **HRMS** (ESI, $[C_{18}H_{34}O_4+Na]^+$): measured 337.2348, theoretical 337.2349.

Reduction of secondary Alcohol:

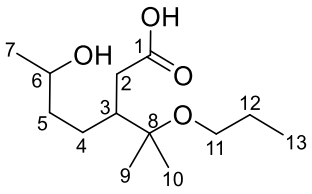


n = 1 **(83)**
n = 6 **(84)**

n = 1 **(85)**
n = 6 **(86)**

Synthesis of 6-hydroxy-3-(2-propoxypropan-2-yl)heptanoic acid **(85)**

To a solution of 6-oxo-3-(2-propoxypropan-2-yl)heptanoic acid **(83)** (1.5 g, 6.14 mmol) in dichloromethane (50 mL) cooled at 0 °C, sodium borohydride (0.26 g, 6.75 mmol) was added portion-wise, and the resulting mixture stirred for 24 h at room temperature. Product formation was checked by TLC. The reaction was quenched by adding (30 mL) of water and extracted with dichloromethane (3 × 80 mL). The combined organic layer was dried over $MgSO_4$ and concentrated to afford the title compound (1.45 g, 96%).

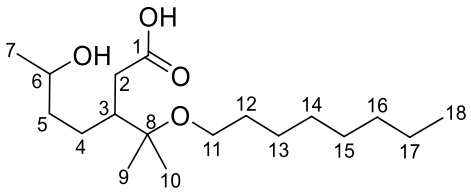


(85)

As a pale yellow oil. $\mathbf{R_f}$(pentene/EtOAc 1:1): 0.28, 0.37; **IR** (KBr, cm^{-1}) $\mathbf{V_{max}}$: 3369, 2963, 2933, 2874, 1705, 1547, 1455, 1370, 1240, 1144, 1074, 1006, 933, 868, 744, 608; δ **^{1}H NMR** (400 MHz, $CDCl_3$) δ 3.87 – 3.75 (m, 1H, H-6), 3.43 – 3.24 (m, 2H, H-11), 2.72 – 2.58 (m, 1H, H-2), 2.27 – 2.16 (m, 1H, H′-2), 2.08 – 1.95 (m, 1H, H-3), 1.82 – 1.55 (m, 1H, H-5), 1.64 – 1.35 (m, 3H, H′-5 and H-12), 1.33 – 1.24 (m, 1H, H-4), 1.23 – 1.19 (m, 6H, H-9 and H-10), 1.18 – 1.12 (m, 1H, H′-4), 1.11 (s, 3H, H-7), 0.91 (t, J = 7.4 Hz, 3H, H-13); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 177.7 (C-1), 77.6, 77.5 (C-8), 68.2, 67.8 (C-6), 62.9, 62.9 (C-11), 44.3, 44.2 (C-C3), 37.7, 37.6 (C-5), 35.7 (C-2), 27.2, 27.0 (C-9), 23.7, 23.6 (C-10), 23.4 (C-7), 23.3 (C-12), 21.1, 21.0 (C-4), 10.7 (C-13); **HRMS** (ESI, $[C_{13}H_{26}O_4+H]^+$): measured 247.1900, theoretical 247.1904.

Synthesis of 6-hydroxy-3-(2-(octyloxy)propan-2-yl)heptanoic acid **(86)**

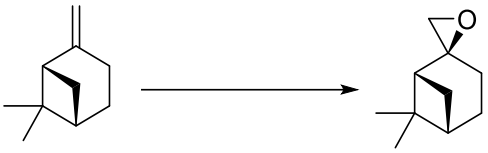
To a solution of 3-(2-(octyloxy)propan-2-yl)-6-oxoheptanoic acid **(84)** (1.5 g, 4.76 mmol) in dichloromethane (60 mL) cooled at 0 °C, sodium borohydride (0.20 g, 5.24 mmol) was added portion-wise and the resulting mixture stirred for 24 h at room temperature. Product formation was checked by TLC. The reaction was quenched by adding (40 mL) of water and extracted with dichloromethane (3 × 100 mL). The combined organic layer was dried over $MgSO_4$ and concentrated to afford the title compound (1.35 g, 89%)



(86)

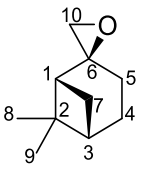
As a pale yellow oil. $\mathbf{R_f}$(pentene/EtOAc 1:1): 0.22; **IR** (KBr, cm^{-1}) $\mathbf{V_{max}}$ 3225, 2921, 2853, 1713, 1478, 1377, 1148, 1083, 846, 781, 722; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 3.84 – 3.75 (m, 1H, H-6), 3.43 – 3.25 (m, 2H, H-11), 2.71 – 2.57 (m, 1H, H-2), 2.27 – 2.10 (m, 1H, H′-2), 1.63 – 1.38 (m, 2H, H-3 and H-12), 1.29 – 1.25 (m, 15H, H′-12, 4, 5, 13, 14, 15, 16 and H-17), 1.24 – 1.15 (m, 6H, H-9 and H-10) 1.10 (s, 3H, H-7), 0.87 (t, J = 7.4 Hz, 3H, H-18); **^{13}C NMR** (101 MHz, CDCl3) δ 177. (C-1), 77.5, 77.4 (C-8), 68.1, 67.8 (C-6), 61.3, 61.2 (C-11), 44.2, 44.1 (C-3), 37.8, 37.6 (C-5), 35.7 (C-2), 31.8 (C-16), 30.2 (C-12), 29.4 (C-9), 29.3 (C-10), 27.2, 27.0 (C-14), 26.2 (C-15), 23.6, 23.5 (C-13), 23.4, 23.3 (C-7), 22.6 (C-17), 21.2, 21.1 (C-4), 14.1 (C-18); **HRMS** (ESI, $[C_{18}H_{36}O_4+H]^+$): measured 317.2696, theoretical 317.2686.

Synthesis of β-pinene oxide **(87)**



(7) **(87)**

(-)-β-pinene **(7)** (8.7 g, 63.9 mmol) was dissolved in acetone (250 mL) with stirring. Sodium bicarbonate (13.41 g, 159.7 mmol) was then added to the solution. A solution of Oxone® (29.44 g, 95.8 mmol) in water (187 mL) was then slowly added to the mixture over a period of 30 minutes with rapid stirring. The mixture was then stirred at room temperature for 3 hours, until starting material consumption was indicated by TLC. The reaction mixture was then quenched (saturated aqueous sodium sulfite, 100 mL) and left to stir for 5 minutes. Organics were then extracted with diethyl ether (3 × 150 mL). The organic fractions were combined and washed with water (100 mL), saturated aqueous sodium bicarbonate (100 mL) and brine 70 mL), then dried ($MgSO_4$). The resulting mixture was filtered under gravity, and the solvent was removed under reduced pressure to yield (9.5 g, 98%) . No further purification was required.

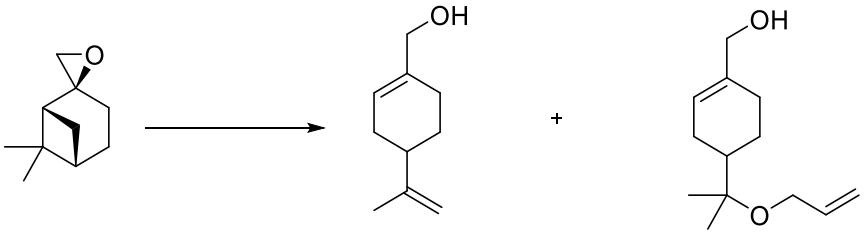


(87)

As a colourless oil. $\mathbf{R_f}$ (petrol:EtOAc 19:1): 0.67; **IR** (KBr) ν_{max}/cm^{-1} 2918, 2869, 1460, 1385, 140, 937, 907; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 2.76 (d, *J* = 5.0 Hz, 1H, H-10), 2.58 (d, *J* = 5.0 Hz, 1H, H-10), 2.28 – 2.23 (m, 1H, H-7), 2.19 – 2.11 (m, 1H, H-5), 2.00 – 1.95 (m, 1H, H-1), 1.92 – 1.76 (m, 2H, H-4), 1.68 (ddd, *J* = 10.8, 7.0, 1.9 Hz, 1H, H-5), 1.65 (d, *J* = 10.3 Hz, 1H,

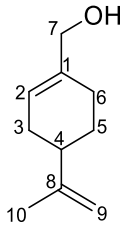
H-7), 1.49 (t, *J* = 5.4 Hz, 1H, H-3), 1.23 (s, 3H, H-9), 0.90 (s, 3H, H-8); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 61.3 (C-6), 56.3 (C-10), 48.8 (C-3), 40.6 (C-2), 40.1(C-1), 26.0 (C-9), 25.1 (C-7), 23.5 (C-5), 22.3 (C-4), 21.1 (C-8); **HRMS** (ESI, $[C_{10}H_{16}O+H]^+$): measured 153.1277, theoretical 153.1274. Spectral data for **87** agrees with what has been reported previously in the Stockman's Group.

Synthesis of (4-(prop-1-en-2-yl)cyclohex-1-en-1-yl)methanol **(88)** and (4-(2-(allyloxy)propan-2-yl)cyclohex-1-en-1-yl)methanol **(91)** and



(87) **(88)** **(91)**

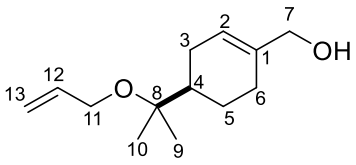
β-pinene oxide (2.0 g, 13.14 mmol) was added dropwise to allyl alcohol (20 mL), followed by the addition of CSA (10 mg, 0.043 mmol) and the reaction mixture was stirred vigorously at room temperature for 4 h. The reaction mixture was diluted using water (20 mL) and the product was extracted using EtOAc (3 x 20 mL). The organic layers were combined and was washed with water (3 x 20 mL) and then brine (20 mL), dried over $MgSO_4$ and the solvent was removed in vacuo. The crude product was purified using silica gel chromatography (hexene:EtOAc 7:3 to afford **(88)** in (1.3 g, 65%).



(88)

As a colorless oil. $\mathbf{R_f}$ (hexene:EtOAc 7:3): 0.62; **IR** (KBr) ν_{max}/cm^{-1} 3325, 2980, 2917, 2820, 1643, 1374, 997, 886; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.69 (brs, 1H, H-2), 4.72 (d, *J* = 4.8 Hz, 2H, H-9), 4.05 – 3.93 (m, 2H, H-7), 2.21 – 2.05 (m, 4H, H-3, H-4 and H-6), 2.00 – 1.80 (m, 2H, H-3 and H-5), 1.74 (s, 3H, H-10), 1.55 – 1.39 (m, 1H, H-5); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 149.8 (C-8), 137.2 (C-1), 122.3 (C-2), 108.7 (C-9), 67.1 (C-7), 41.2 (C-4), 30.4 (C-3), 27.5 (C-5), 26.1 (C-6), 20.8 (C-10); **HRMS** (ESI, $[C_{10}H_{16}O+H]^+$): measured 153.1264, theoretical 153.1260.

β-pinene oxide (2.0 g, 13.14 mmol) was added dropwise to allyl alcohol (10 mL), followed by the addition of PTSA (4 mg, 0.02 mmol) and the reaction mixture was stirred vigorously at room temperature for 48 h. The reaction mixture was diluted using water (20 mL) and the product was extracted using EtOAc (3 x 20 mL). The organic layers were combined and was washed with water (3 x 20 mL) and then brine (20 mL), dried over $MgSO_4$ and the solvent was removed in vacuo. The crude product was purified using silica gel chromatography (hexene:EtOAc 7:3 to afford **(91)** in (0.8 g, 29%).

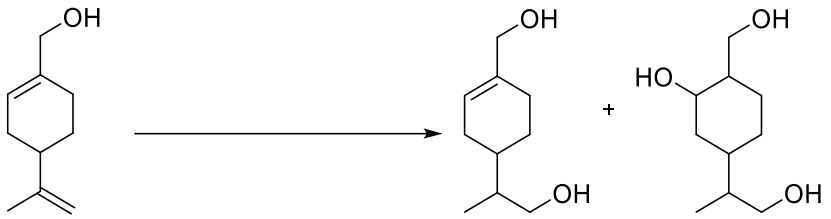


(91)

As a colorless oil. $\mathbf{R_f}$ (hexene:EtOAc 7:3): 0.51; **IR** (KBr) ν_{max}/cm^{-1} 3368, 2960, 2921, 2911, 1725, 1136, 993, 917, 812 ;**^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.98 – 5.86 (m, 1H, H-12), 5.70 (brs, 1H, H-2), 5.28 (dq, *J* = 17.2, 1.8 Hz, 1H, H-13), 5.11 (dq, *J* = 10.4, 1.6 Hz, 1H, H-13), 4.00 (s, 2H, H-7), 3.91 (dt, *J* = 5.3, 1.6 Hz, 2H, H-11), 2.09-2.03 (m, 2H, H-3 and H-6), 1.97-1.86 (m, 3H, H-3, H-6 and H-4), 1.32 – 1.22 (m, 2H, H-5), 1.16 (s, 3H, H-9) 1.15 (s, 3H, H-10); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 137.4 (C-1), 136.3 (C-12), 122.8 (C-2), 115.4 (C-13), 76.9

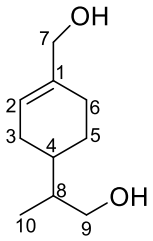
(C-8), 67.2 (C-11), 62.2 (C-7), 42.3 (C-4), 26.7 (C-9), 26.5 (C-10), 23.7 (C-3), 22.8 (C-6), 22.6(C-5); **HRMS** (ESI, $[C_{13}H_{22}O_2+Na]^+$): measured 233.1508, theoretical 233.1512.

Synthesis of 2-(4-(hydroxymethyl)cyclohex-3-en-1-yl)propan-1-ol **(89)** and 2-(hydroxymethyl)-5-(1-hydroxypropan-2-yl)cyclohexan-1-ol **(90)**



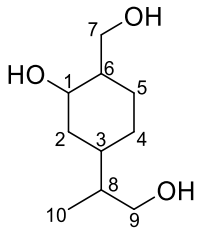
(88) **(89)** **(90)**

To a cold solution (0 °C) of **(88)** (2.5 g, 16.42 mmol) in THF (6.5 mL), $BH_3.SMe_2$ (8.2 mL, 19.70 mmol, 2M in THF) was added dropwise and the mixture was stirred at 0 °C for 1 hour. After that time, keeping the solution at 0 °C, EtOH (8 mL), NaOH (8.5 mL, 1M in H_2O) and H_2O_2 (4 mL, 30% v/v in H_2O) were added subsequently in a dropwise manner. The resulting mixture was stirred for 2 hours, warming to room temperature and additionally two hours at 80 °C. The reaction was then allowed to cool before quenching by addition of a saturated aqueous solution of NH_4Cl. The aqueous layer was extracted with Et_2O (3x). Combined organic layers were washed with brine, dried, and the solvent was evaporated, and the crude was purified by flash chromatography using a pentene/EtOAc (1:1) to afford **(89)** in (1.85 g, 66%) and **(90)** in (0.33 g, 11%).



(89)

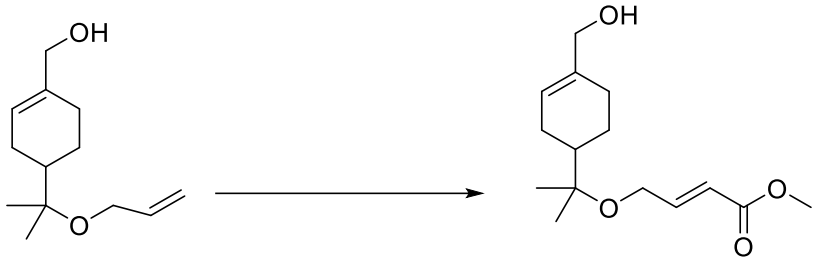
As a colorless oil; $\mathbf{R_f}$ (pentene/EtOAc 1:1) 0.29; **IR** (KBr) v_{max}/cm^{-1} 3320, 2918, 2880, 1711, 1249, 1029, 636; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.68 – 5.58 (m, 1H, H-2), 3.93 (d, *J* = 2.5 Hz, 2H, H-7), 3.60 – 3.50 (m, 1H, H-9), 3.46 – 3.40 (m, 1H, H-9), 2.67 – 2.38 (m, 4H, H-3 and H-6), 1.82 – 1.66 (m, 3H, H-4, H-5 and H-8), 1.62 – 1.47 (m, 1H, H-5), 0.94 – 0.74 (m, 3H, H-10); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 137.5 137.4 (C-1), 122.4, 122.3 (C-2), 66.9 (C-7), 66.0, 65.9 (C-9), 39.9 ,39.8 (C-8), 35.3, 35.2 (C-4), 29.5 27.2 (C-3), 26.8, 26.3, (C-5), 26.1 ,25.0 (C-6), 13.5, 13.2 (C-10); **HRMS** (ESI, $[C_{10}H_{18}O_2+Na]^+$): measured 193.1203, theoretical.



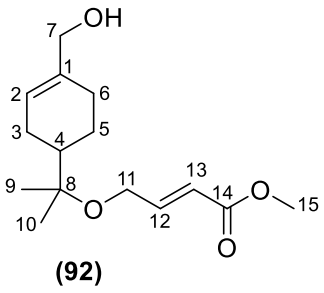
(90)

As a colorless oil; $\mathbf{R_f}$ (pentene/EtOAc 1:1) 0.17; **IR** (KBr) v_{max}/cm^{-1} 3342, 2924, 2866, 1718, 1242, 1035, 609; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 3.64 – 3.37 (m, 4H, H-7 and H-9), 3.37 – 3.37 (m, 1H, H-1), 2.61 – 2.28 (m, 2H, H-2 and H-5), 1.89 – 1.79 (m, 1H, H-6), 1.72 – 1.64 (m, 1H, H-2), 1.56 – 1.33 (m, 5H, H-5, 4, 3 and H-8), 0.93 – 0.80 (m, 3H, H-10); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 71.6 (C-1), 71.2 (C-9), 65.9 (C-7), 40.4 (C-6), 39.2 (C-8), 33.7 (C-2), 33.6 (C-4), 25.2 (C-3), 23.3 (C-5), 13.6 (C-10); **HRMS** (ESI, $[C_{10}H_{20}O_3+Na]^+$): measured 211.1316 , theoretical 211.1305.

Synthesis of methyl (E)-4-((2-(4-(hydroxymethyl)cyclohex-3-en-1-yl)propan-2-yl)oxy)but-2-enoate **(92)**



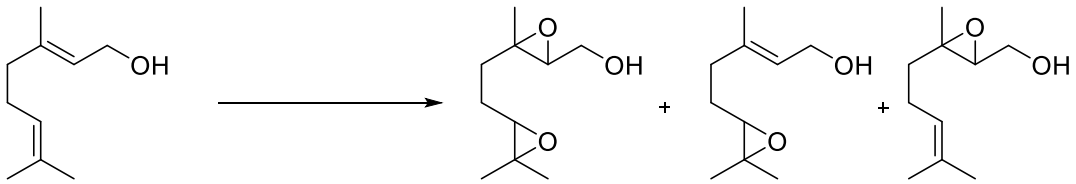
A round-bottom flask with a stir bar was oven dried and then flushed with nitrogen for 15 min. Methyl acrylate (1.02 g, 11.9 mmol), Grubbs' second-generation catalyst (0.075 g, 0.119 mmol), and CuI (0.027g , 0.142 mmol) were charged into the flask under a positive flow of nitrogen, and to this mixture was added dry DCM (10 mL) ,**(91)** (0.5 g, 2.38 mmol) was added, and the mixture was allowed to reaction at room temperature. After completion of the reaction, the solvents were evaporated, and the crude mixture was purified by flash chromatography using a pentene/EtOAc (7:3) to afford **(92)** in (0.6 g, 94%).



As a colorless oil; $\mathbf{R_f}$ (hexene:EtOAc 7:3) 0.21; **IR** (KBr) ν_{max}/cm^{-1} 3400, 2972, 2922, 2841, 1721, 1661, 1435, 1384, 1365, 1300, 1281, 1193, 1165, 1136, 1115, 1021, 999, 966, 916, 812; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 6.94 (dt, *J* = 15.6, 3.9 Hz, 1H, H-12), 6.04 (dt, *J* = 15.6, 2.2 Hz, 1H, H-13), 5.64 – 5.59 (m, 1H, H-2), 4.01 (dd, *J* = 3.9, 2.2 Hz, 2H, H-7), 3.94 – 3.90 (m, 2H, H-11), 3.67 (s, 3H, H-15), 2.24 – 2.02 (m, 4H, H-3 and H-6), 1.88 – 1.76 (m, 2H, H-4 and H-5), 1.65 (m, 1H, H-5), 1.09 (s, 3H, H-9), 1.07 (s, 3H, H-10); **^{13}C NMR** (101 MHz, CDCl3) δ

166.9 (C-14), 146.4 (C-12), 137.5 (C-1), 122.1 (C-13), 119.7 (C-2), 77.2 (C-8), 66.8 (C-11), 59.9 (C-7), 51.3 (C-15), 42.7 (C-4), 26.5 (C-10), 26.3 (C-9), 23.5 (C-3), 22.5 (C-6), 22.3 (C-5); **HRMS** (ESI, $[C_{15}H_{24}O_4+Na]^+$): measured 291.1564, theoretical 291.1567.

Synthesis (3-(2-(3,3-dimethyloxiran-2-yl)ethyl)-3-methyloxiran-2-yl)methanol **(93)** , (E)-5-(3,3-dimethyloxiran-2-yl)-3-methylpent-2-en-1-ol **(94)** and (3-methyl-3-(4-methylpent-3-en-1-yl)oxiran-2-yl)methanol **(95)**

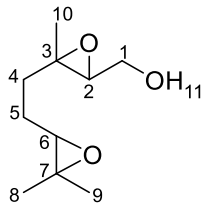


(70) **(93)** **(94)** **(95)**

Method 1: To a well-stirred and cooled (-5 °C) mixture of geraniol **(70)** (4.40 g, 28.53 mmol) in sodium bicarbonate solution (0.5 M, 115 mL) was added in small portions *m*CPBA (20.8 g, 119.8 mmol) and stirred at room temperature for 2.5 hours until starting material consumption was indicated by TLC. Then, a mixture was saturated with NaCl and extracted with CH_2Cl_2 (3 × 150 mL). The organic fractions were combined and washed with saturated NaS_2O_3(150 mL), then dried ($MgSO_4$). The resulting mixture was filtered and the solvent was removed under reduced pressure to afford **(93)** in (4.19 g, 79%).

Method 2: Geraniol **(70)** (2.64 g, 15.64 mmol) was dissolved in acetone (76 mL) with stirring. Sodium bicarbonate (6.60 g, 78.2 mmol) was then added to the solution. A solution of Oxone® (12.0 g, 39.1 mmol) in water (56 mL) was then slowly added to the mixture over a period of 30 minutes with rapid stirring. The mixture was then stirred at room temperature for 4 hours. The reaction mixture was then quenched (saturated aqueous sodium sulfite, 100 mL) and left to stir for 5 minutes. Organics were then extracted with diethyl ether (3 × 60 mL). The organic

fractions were combined and washed with water (50 mL), saturated aqueous sodium bicarbonate (50 mL) and brine (50 mL), then dried over $MgSO_4$. The resulting mixture was filtered under gravity, and the solvent was removed under reduced pressure, then the resulting product was purified by column chromatography (diethyl ether: petroleum ether 3:1) to afford **(93)** in (2.46 g, 85%).

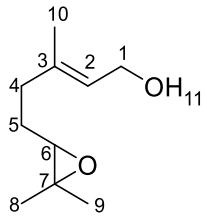


(93)

As a colourless oil and as a (1:1) mixture of diastereomers. $\mathbf{R_f}$ (petrol:diethylether 1:1): 0.13; **IR** (KBr, cm^{-1}) 3432, 2963, 2927, 1457, 1380, 1249,1033, 868, 676; **^{1}H NMR** (400 MHz, CDCl3) δ 3.78 – 3.61 (m, 2H, H1), 2.95 (t, *J* = 4.9 Hz, 1H, H2), 2.74 – 2.66 (m, 1H, H6), 1.87 – 1.67 (m, 2H, H4), 1.64 – 1.45 (m, 2H, H5), 1.29 – 1.22 (m, 9H, H8, H9 and H10).; **^{13}C NMR HRMS** 13C NMR (101 MHz, CDCl3) δ 64.2, 63.8 (C-2), 62.9, 62.6 (C-6), 61.1, 60.8 (C-1), 60.7, 60.5 (C-3), 58.8, 58.7, (C-7), 35.9, 35.0 (C-4), 24.8 (C-10), 24.6, 24.4 (C-5), 18.7, 18.6 (C-9), 16.8, 16.4 (C-8); **HRMS** (ESI, $[C_{10}H_{18}O_3+Na]^+$)measured 209.1152, theoretical 209.1148.

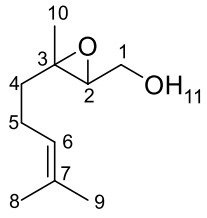
Geraniol **(70)** (9.0 g, 58.34 mmol) was dissolved in acetone (250 mL). Sodium bicarbonate (12.25 g, 145.85 mmol) was then added to the solution. A solution of Oxone® (30.46 g, 99.18 mmol) in water (188 mL) was then slowly added to the mixture over a period of 30 minutes with rapid stirring. The mixture was then stirred at room temperature for 4 hours. The reaction mixture was then quenched (saturated aqueous sodium sulfite, 150 mL) and left to stir for 5 minutes. Organics were then extracted with diethyl ether (3 × 200 mL). The organic fractions

were combined and washed with water (150 mL), saturated aqueous sodium bicarbonate (100 mL) and brine (150 mL), then dried over $MgSO_4$. The resulting mixture was filtered under gravity, and the solvent was removed under reduced pressure, then the resulting product was purified by column chromatography (diethyl ether:petroleum ether 3:1) to afford **(93)** (2.0 g, 18%), **(94)** in (5.0 g, 50%), and **(95)** in (0.3 g, 3%).



(94)

As a colorless oil. $\mathbf{R_f}$ (petrol:diethylether 1:1): 0.21; ; **IR** (KBr) ν_{max}/cm^{-1} 3407, 2960, 2925, 2870, 1450, 1383, 1030, 862; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.36 (t, *J* = 1.3 Hz, 1H, H-2), 4.05 (d, *J* = 2.1 Hz, 2H, H-1), 2.66 (t, *J* = 5.7 Hz, 1H, H-6), 2.18 – 1.99 (m, 2H, H-5), 1.61 (s, 3H, H-10), 1.60 – 1.51 (m, 2H, H-4), 1.23 (s, 3H, H-9), 1.19 (s, 3H, H-8); **^{13}C NMR** (101 MHz, $CDCl_3$)) δ 137.7 (C-3), 124.3 (C-2), 64.0 (C-6), 58.9 (C-1), 58.4 (C-7), 36.2 (C-4), 27.0 (C-5), 24.7 (C-9), 18.6 (C-8), 16.1 (C-10); **HRMS** (ESI, $[C_{10}H_{18}O_2+Na]^+$): measured 193.1192, theoretical 193.1199.

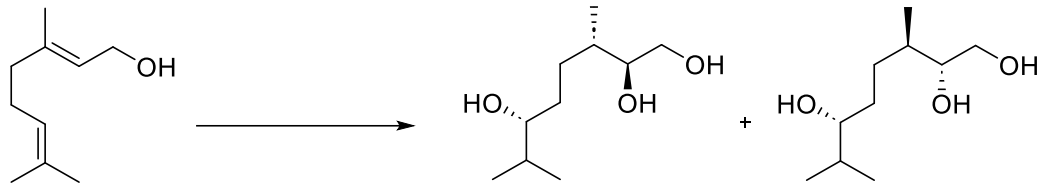


(95)

As a colorless oil. $\mathbf{R_f}$ (petrol:diethylether 1:1): 0.32; **IR** (KBr) ν_{max}/cm^{-1} 3396, 2965, 2926, 1710, 1448, 1379, 1116, 998, 869, 677; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.07 (t, *J* = 7.1 Hz, 1H,

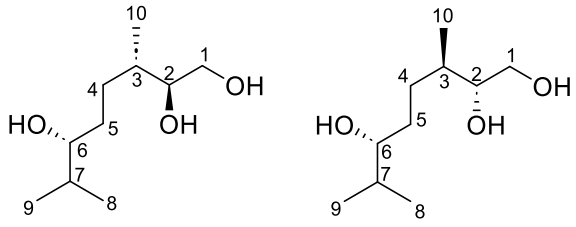
H-6), 3.87 – 3.74 (m, 1H, H-1), 3.70 – 3.59 (m, 1H, H´-1), 2.97 (dd, *J* = 6.8, 4.1 Hz, 1H, H-2), 2.68 (br, 1H, H-11), 2.13 – 2.02 (m, 2H, H-5), 1.70 – 1.64 (m, 4H, H-8 and H-4), 1.60 (s, , 3H, H-9), 1.54 – 1.40 (m, 1H, H-4), 1.29 (s, 3H, H-10).; **^{13}C NMR** (101 MHz, $CDCl_3$) δ 132.1 (C-7), 123.3 (C-6), 63.2 (C-2), 61.4 (C-3), 61.2 (C-1), 38.5 (C-4), 25.6 (C-5), 23.7 (C-9), 17.6 (C-8), 16.7 (C-10); **HRMS** (ESI, $[C_{10}H_{18}O_2+Na]^+$): measured 193.1193, theoretical 193.1199.

Synthesis of (2S,3S,6R)-3,7-dimethyloctane-1,2,6-triol **(96a)** and (2R,3R,6R)-3,7-dimethyloctane-1,2,6-triol **(96b)**



(70) **(96a)** **(96b)**

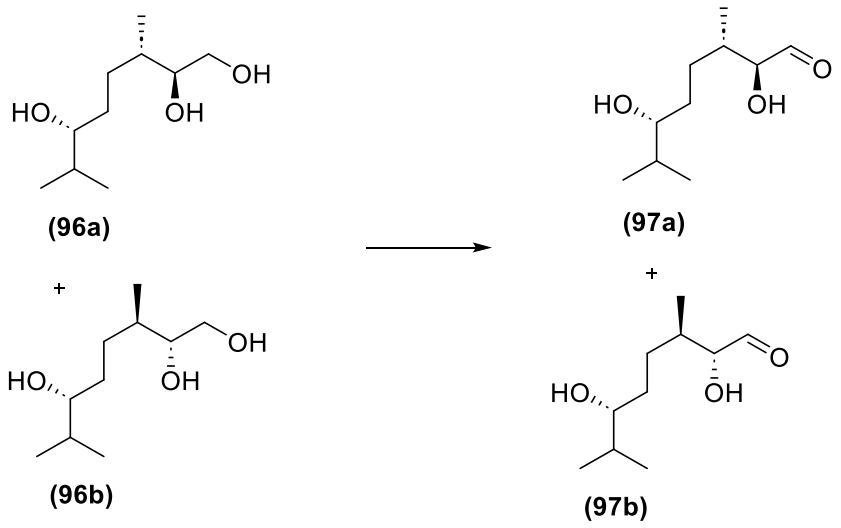
To a cold solution 0 ℃ of **(70)** (5g, 32.41mmol) in THF (15 mL), BH_3*SMe_2 (37.3 mL, 74.54 mmol, 2M in THF) was added dropwise and the mixture was stirred at 0 ℃ for 2 hour. After that time, keeping the solution at 0 ℃, EtOH (37 mL), NaOH (40 mL, 1M in H_2O) and H_2O_2 (18 mL, 30% v/v in H_2O) were added subsequently in a dropwise manner. The resulting mixture was stirred for 1 hour warming to room temperature and additionally two hours at 80 ℃. The aqueous layer was extracted with EtOAc (3x). Combined organic layers were washed with brine, dried, and the solvent was evaporated to yield (3.9 g, 63%).



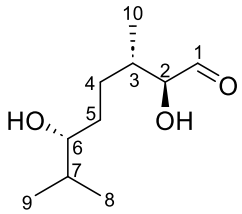
(96a) **(96b)**

As a colourless oil. **R_f** (hexene/EtOAc 1:1): 0.27; **IR** (KBr) ν_{max}/cm^{-1} 3344, 2958, 2926, 2890, 1378, 1047, 608; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 3.63 – 3.45 (m, 3H), 3.23 – 3.19 (m, 1H), 1.50 (m, 6H), 1.31 (m, 5H), 1.07 – 0.99 (m, 4H), 0.84 – 0.73 (m, 9H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 76.26, 71.33, 71.19, 60.42, 39.78, 39.73, 39.57, 33.60, 33.50, 33.37, 33.31, 33.20, 32.78, 31.45, 31.38, 29.70, 29.02, 22.49, 19.67, 19.47, 19.37, 18.74, 18.68, 17.34, 17.23, 17.00, 16.95, 14.80, 13.89; **HRMS** (ESI, $[C_{10}H_{22}O_3+Na]^+$): measured 213.1458, theoretical 213.1461.

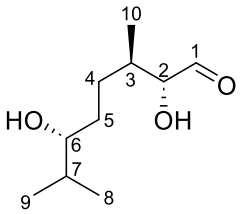
Synthesis of (2S,3S,6R)-2,6-dihydroxy-3,7-dimethyloctanal **(97a)** and (2R,3R,6R)-2,6-dihydroxy-3,7-dimethyloctanal **(97b)**



A solution of triol **(96a)** and **(96b)** (1g, 5.26 mmol), TEMPO (0.08 g, 0.53 mmol), TBACl (1.41 g, 0.53 mmol), and an appropriate amount of an internal standard in 50 mL of dichloromethane and 50 mL of an aqueous solution of $NaHCO_3$ (0.5 M) and K_2CO_3 (0.05 M) were vigorously stirred at room temperature. The solid of NCS (1.05 g, 7.89 mmol) was then added. Stirring was for 48 h. After the organic layer was separated, the aqueous phase was extracted with DCM (2 × 100 mL). The dichloromethane extracts were washed with brine (1 × 100 mL), dried, and evaporated. then the resulting product was purified by column chromatography (pentene/EtOAc 2:1) to afford **(97a)** and **(97b)** in (0.61 g, 62%).



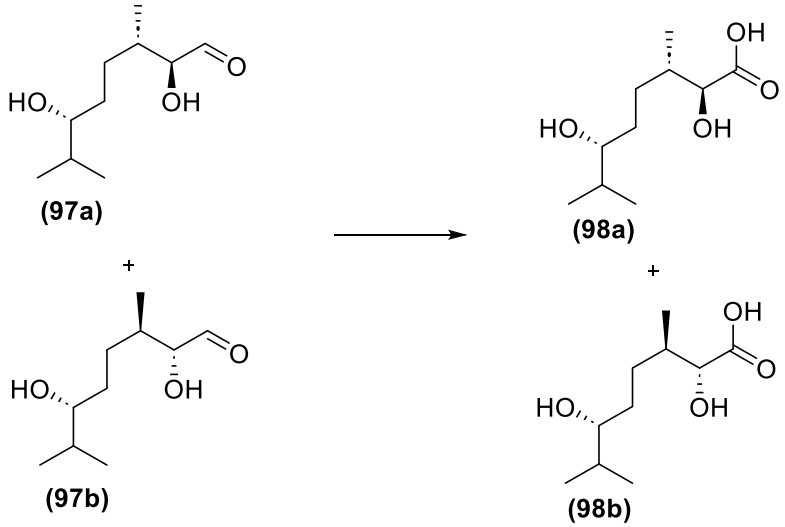
(97a)



(97b)

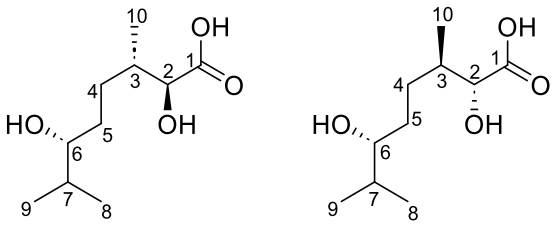
As a pale yellow oil. **R_f** (pentene/EtOAc 2:1): 0.47; **IR** (KBr) ν_{max}/cm^{-1} 3435, 2958, 2933, 1723, 1462, 1374, 1244, 1099,1045. 1016, 912, 847, 786, 730;**^{1}H NMR** (400 MHz, $CDCl_3$) δ 9.79 (d, *J* = 2.2 Hz, 1H, H-1), 5.31 – 5.07 (m, 1H, OH), 4.17 (m, 1H, OH), 3.78 – 3.54 (m, 1H, H-2), 3.40 – 3.37 (m, 1H, H-6), 2.49 – 2.40 (m, 1H, H-7), 2.34 – 2.23 (m, 1H, H-3), 2.16 – 2.05 (m, 2H, H-5), 1.71 – 1.61 (m, 4H, H-4), 1.00 (d, *J* = 4.9 Hz, 3H, H-10), 0.96 (s, 3H, H-8), 0.94 (s, 3H, H-9); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 203.1 (C-1), 76.8, 76.5 (C-6), 51.2, 51.0 (C-2), 33.6, 33.5 (C-7), 33.3, 33.1 (C-3), 31.5, 31.3 (C-5), 28.4, 27.9 (C-4), 20.1, 19.9 (C-8), 18.9, 18.8 (C-9), 17.2, 17.0 (C-10); **HRMS** (ESI, [$C10H_{20}O_3$-H]-): measured 187.1341, theoretical 187.1340.

Synthesis of (2S,3S,6R)-2,6-dihydroxy-3,7-dimethyloctanoic **(98a)** acid and (2R,3R,6R)-2,6-dihydroxy-3,7-dimethyloctanoic acid **(98b)**.



A solution of 80% sodium chlorite (1.7 g, 18.62 mmol) and NaH_2PO_4 (2.7 g 22.61 mmol) in distilled water (20 mL) was added dropwise to a stirred mixture of **(97a and 97b)** (0.5 g 2.66

mmol)**,** and 2-methylbut-2-ene (4 mL) in acetone (17 mL) over 5 h at ambient temperature. The mixture was stirred for another 3 h at ambient temperature. After the reaction was finished, as detected by TLC, the acidic products were extracted with (3× 50 mL) of EtOAc. The organic phase was combined and dried over $MgSO_4$. Evaporation of solvent under reduced pressure, to afford **(98a)** and **(98b)** in (0.32 g, 60%)

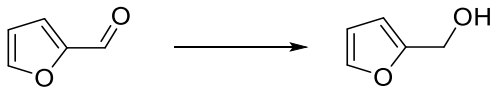


(98a) **(98b)**

As pale yellow oil; $\mathbf{R_f}$ (pentene/EtOAc 1:2): 0.62; **IR** (KBr) v_{max}/cm^{-1} 3401, 2959, 2935, 2874, 1707, 1462, 1382, 1248, 1211, 1171, 1133, 1092, 1058, 996, 955, 884, 677,613, 464; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 4.06 – 3.98 (m, 1H, H-2), 3.36 – 3.29 (m, 1H, H-6), 2.36 – 2.26 (m, 1H, H-7), 2.17 – 2.11 (m, 1H, H-3), 1.48 (d, *J* = 6.7 Hz, 2H, H-5), 1.27 (d, J = 7.7 Hz, 3H, H-4), 0.96 – 0.94 (m, 3H, H-10), 0.90 – 0.88 (m, 6H, H-8 and H-9); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 177.7, 177.8 (C-1), 76.9 (C-6), 76.5 (C-2), 33.4, 33.3 (C-3), 32.9, 32.7 (C-7), 31.3, 31.0 (C-5), 30.3, 29.9 (C-4), 26.3, 24.6 (C-8), 20.1 ,19.8 (C-9), 18.8, 17.2 (C-10); **HRMS** (ESI, [$C_{10}H_{20}O_4$-H]-): measured 203.1292, theoretical 203.1289.

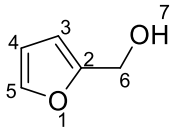
6.2 Synthesis of Chapter three:

Synthesis furan-2-ylmethanol **(99)**[139]



(52) **(99)**

To a solution of **(52)** (11.6 g, 120.7 mmol) in methanol (100 mL) cooled at 0 °C. Sodium borohydride (5.48 g, 144.8 mmol) was added portion-wise to the resulting mixture and stirred for 4 h at room temperature. Product formation was checked by TLC. The reaction was quenched by adding (60 mL) of water and extracted with ethyl acetate (3 × 100). The collected organic layer was dried over $MgSO_4$ and concentrated.



(99)

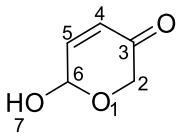
As a yellow oily compound (11 g, 93% yield). $\mathbf{R_f}$ (Cyclohexene:EtOAc 3:7): 0.25; **IR** (KBr, cm^{-1}) $\mathbf{V_{max}}$ 3317, 2927, 2872, 1561, 1258, 1054, 956, 813, 741; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.38 (dd, J = 2.0, 0.9 Hz, 1H, H-5), 6.32 (dd, J = 3.2, 1.9 Hz, 1H, H-4), 6.27 – 6.24 (m, 1H, H-3), 4.53 (s, 2H, H-6), 3.31 (brs, 1H, H-7); **^{13} C NMR** (101 MHz, $CDCl_3$) δ 154.1 (C-2), 142.5 (C-5), 110.4 (C-3), 107.7 (C-4), 57.11 (C-6); **HRMS** (ESI, $[C_5H_6O_2+Na]^+$): measured 121.0263, theoretical 121.0260.

Synthesis 6-hydroxy-2*H*-pyran-3(6*H*)-one **(100)**

(99) **(100)**

Method A: Furan-2-ylmethanol **(99)** (2.2 g, 22.43 mmol) was dissolved in THF (30 mL) and water (7.5 mL), and cooled to 0 °C. To the reaction was added solid $NaHCO_3$ (3.77 g, 44.86 mmol) and NaOAc (1.84 g, 22.43 mmol). *N*-Bromosuccinimide (4.19 g, 23.55 mmol) was then added in small portions while stirring vigorously. The reaction was stirred for 2h, after which TLC indicated complete consumption of the starting material, and the reaction was quenched with ice-cold water (25 mL). The reaction was then extracted with Et_2O (3 x 40 mL), the combined aqueous layers were dried over $MgSO_4$ and concentrated under reduced pressure. The crude residue was purified by column chromatography (hexane/EtOAc, 4:1) to afford **(100)** in (1.27 g, 50%).

Method B: To a stirred solution of the **(99)** (2.2 g, 22.43 mmol) in THF (88 mL) and H_2O (22 mL) were added potassium bromide (0.27 g, 2.24 mmol), $NaHCO_3$ (0.19 g, 2.80 mmol), and oxone (8.27 g, 26.92 mmol) at 0 °C. After completion of the addition, the reaction was allowed to stir at 0 °C for 30 min. The reaction was quenched by adding saturated aqueous $NaHCO_3$ (60 mL) and EtOAc (3 × 100 mL). The combined organic fractions were washed with brine, dried over $MgSO_4$, and concentrated under reduced pressure to afford **(100)** in (2.2 g, 85%).



(100)

As a yellow oil. **R_f** (hexane/EtOAc, 4:1): 0.15; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 6.93 (dd, *J* = 10.2, 3.8 Hz, 1H, H-5), 6.09 (d, *J* = 10.3 Hz, 1H, H-4), 5.58 (d, *J* = 3.8 Hz, 1H, H-6), 5.01 (brs, 1H, OH), 4.50 (d, *J* = 16.1 Hz, 2H, H-2); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 195.4 (C-3), 147.1 (C-4), 127.8 (C-5), 88.3 (C-6), 66.5 (C-2); **HRMS** (ESI, $[C_5H_6O_3+Na]^+$): measured 137.0219, theoretical 137.0209.

Synthesis 5-hydroxy-5,6-dihydro-2H-pyran-2-one **(102)**

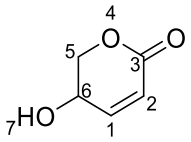
(100) **(102)**

Method A: To a dried flask was added **(100)** (3.00 g, 27.2 mmol), $[Ir(COD)Cl]_2$ (0.46 g, 0.68 mmol), 2,6-dichlorobenzoic acid (2.60 g, 13.60 mmol) in (60 mL) of $CHCl_3$ under nitrogen. The reaction was stirred at room temperature for 18 hours, the solvent was evaporated and the residue was purified by flash column chromatography (hexene:EtOAc 1:1) to obtain **(102)** in (3.0 g, 97%).

Method B step 1: To flask was added **(100)** (0.50 g, 4,38 mmol) in (30 mL) of acetone at 0 °C, then wad added Jones reagent (5 mL, 2.5 M) dropwise for 30 min. After the TLC showed the complete the reaction quenched by slow addition of *i*POH (1.5 mL) at 0°C. The mixture was filtered through a pad of Celite and washed with diethyl ether. The filtrate was washed with brine (2 × 10 mL). The organic layer was dried over $MgSO_4$., filtered and concentrated under reduced pressure to afford **(101)** as an unstable product in (0.23 g, 47 %). **^{1}H NMR** (400

MHz, $CDCl_3$) δ 6.92 (d, *J* = 10.3 Hz, 1H, H-2), 6.85 (d, *J* = 10.3 Hz, 1H, H-1), 4.98 (s, 2H, H-5).

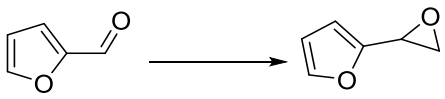
Method B step 2: To solution **(101)** (0.4 g, 3.57 mmol) in (10 mL) of MeOH then was added $CeCl_3.7H_2O$(1.61 g, 3.93 mmol) the reaction mixture cooled to 0 °C , It was followed by portion-wise addition $NaBH_4$ (0.15 g, 3.93 mmol), the reaction mixture keep stirring for 1.3 h. After the TLC showed the complete the reaction, The volume of the reaction mixture was reduced by evaporation and the resultant residue was extracted with (3 × 50 mL), washed with water, brine and dried over $MgSO_4$,filtered and concentrated under reduced pressure to afford **(102)** in (0.16 g, 39 %).



(102)

As a yellow oily. $\mathbf{R_f}$ (hexane:EtOAc,1:1): 0.17; **IR** (KBr, cm^{-1}) $\mathbf{V_{max}}$ 3392, 2922, 1712, 1627, 1237, 1099, 1083, 1011, 826; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 6.96 (dd, *J* = 10.0, 3.6 Hz, 1H, H-2), 5.99 (d, *J* = 9.9 Hz, 1H, H-1), 4.49 – 4.29 (m, 3H, H-5 and H-6); **^{13} C NMR** (101 MHz, $CDCl_3$) δ 163.8 (C-3), 147.2 (C-1), 121.4 (C-2), 72.0 (C-5), 60.5 (C-6); **HRMS** (ESI, $[C_5H_6O_3+Na]^+$): measured 137.0217, theoretical 137.0209.

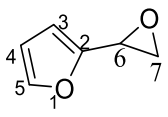
Synthesis 2-(oxiran-2-yl)furan **(104)**



(52) **(104)**

Method A: In a three-necked round bottom flask equipped with stirrer and nitrogen atmosphere a mixture of (11.6 g, 120.7 mmol) of furfural, (13.54 g, 120.7 mmol) of trimethylsulfonium iodide, (13.54 g, 241.4 mmol) of potassium hydroxide, (0.6 g, 30.2 mmol) of distilled water and (150 mL) acetonitrile was stirred vigorously and heated at 60 °C for 3 hours. After this time the reaction mixture was allowed to cool at room temperature. The solid formed was filtered and solution was concentrated under reduced pressure. The residue was diluted with anhydrous ether and more KI precipitated. This action was repeated until no more KI was collected. The filtrate was dried by $MgSO_4$, and the solvent evaporated to obtain **(104)** in (3.41 g, 86%).

Method B: In a round bottom flask equipped with stirrer and a mixture trimethyl sulfonium iodide (6.37 g, 31.22 mmol), and sodium hydride (0.75 g, 31.22 mmol). The flask was evacuated and refilled 3x with nitrogen, and anhydrous DMSO (20 mL) and THF (16 mL) were added, and the reaction was stirred for 20 minutes at room temperature. The solution was then cooled to 0 °C and (1.5 g, 15.61 mmol) of furfural in THF (10 mL) was added at 0 °C and allowed to stir until consumption of aldehyde by TLC. The reaction was diluted with water (30 mL) and extracted with Et_2O (30 ml x 4). The combined organic layers were washed with water (10 mL) and brine (10 mL x 2), dried over $MgSO_4$, and concentrated under reduced pressure to obtain **(104)** in (0.8 g, 46%).

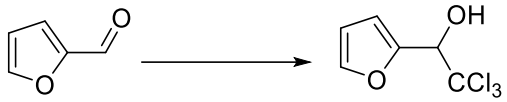


(104)

As a yellow oil. $\mathbf{R_f}$ (hexane:Et_2O 4:1): 0.4; **IR** (KBr, cm^{-1}) $\mathbf{V_{max}}$ 3066, 2295, 1669, 1415, 928, 863, **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.31 (dd, *J* = 1.7, 1 Hz, 1H, H-5), 6.37 (dd, *J* = 3.4, 1.7

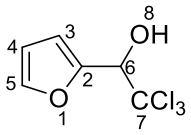
Hz, 1H, H-4), 6.29 (dd, *J* = 3.4, 1.0 Hz, 1H, H-3), 3.80 (dd, *J* = 8.0, 7.7 Hz, 1H, H-6), 3.17 (dd, *J* = 7.8, 4.3 Hz, 2H, H-7). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 150.2 (C-2), 142.9 (C-5), 110.8 (C-3), 109.9 (C-4), 47.9 (C-6), 46.4 (C-7).

Synthesis of 2,2,2-trichloro-1-(furan-2-yl)ethan-1-ol **(108)**



(52) **(108)**

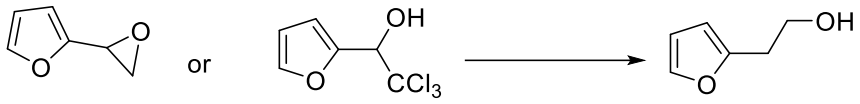
A mixture of **(52)** (11.6 g, 120.72 mmol) and chloroform (19.34 mL, 241.44 mmol) was added dropwise under nitrogen of DBU (18.02 mL, 120.72 mmol). The reaction was stirred for 4 h, diluted with chloroform (120 mL), and washed with 2 N HCl (3 × 100 mL) to remove the catalyst. The organic phase was then dried with $MgSO_4$ and evaporated. The crude material was purified by flash chromatography with indicated ratios of EtOAc:hexanes 95:5 to afford **(108)** in (16.87 g, 65%).



(108)

As a yellow oil compound; **R_f** (hexane:EtOAe 95:5); **IR** (KBr, cm^{-1}) 3396, 2923, 1259, 818, 739; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.49 (dd, *J* = 1.9, 0.8 Hz, 1H, H-5), 6.63 (d, *J* = 3.4 Hz, 1H, H-3), 6.46 (dd, *J* = 3.4, 1.8 Hz, 1H, H-4), 5.26 (s, 1H, H-6), 3.44 (brs, 1H, H-8); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 148.5 (C-2), 143.1 (C-5), 110.9 (C-3), 110.7 (C-4), 101.3 (C-7), 79.3(C-6).

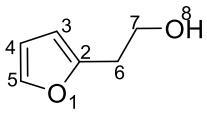
Synthesis 2-(furan-2-yl)ethan-1-ol **(105)**



(104) **(108)** **(105)**

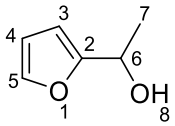
Method A: To a stirred solution of (**104)** (6 g, 54.50 mmol) in ethanol (300 mL), sodium borohydride (2.06 g, 54.50 mmol) was added in portions under nitrogen atmosphere. The reaction mixture was stirred for 18 h at room temperature after the reaction was completed and hydrolysed with (50 mL) of water. The resulting solution was extracted with ether (3 × 100 mL), and the organic layer was dried over $MgSO_4$ and concentrated under reduced pressure. The crude was purified by column chromatography (pentane: EtOAc 2:1) in (3.0 g, 49%) of **(105)** and (1.62 g, 27%) of **(107)** yield.

Method B step 2: A **(108)** (16.5 g, 76.58 mmol) was added to a dry 500 mL two-neck round-bottomed flask equipped with a magnetic stir bar and a reflux condenser under nitrogen. Anhydrous IPA (300 mL) was then added, followed by the addition of $LiBH_4$ (6.67 g, 306.32 mmol) and freshly powdered NaOH (9.2 g, 229.74 mmol). The reaction mixture was heated to 85 °C and allowed to react at this temperature for 18 h. After completion of the reaction, as indicated by TLC, the reaction mixture was cooled to room temperature and quenched with aqueous NH_4Cl (500 mL). The resulting aqueous phase was saturated with solid NaCl, and the product was extracted with ethyl acetate (5×300 mL). The organic phase was dried by $MgSO_4$, filtered, and concentrated under reduced pressure. The crude material was purified by flash chromatography with indicated ratios of EtOAc:hexanes to afford the **(105)** in (7.4 g, 86%).



(105)

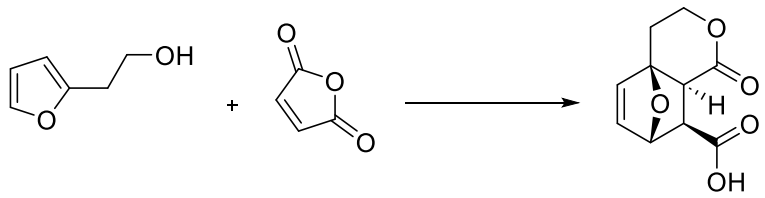
As a yellow oil; **R_f** (hexane:EtOAe 7:3): 0.47; **IR** (KBr, cm^{-1}) 3340, 3120, 2950, 2920, 1724, 1597, 1506, 1422, 1338, 1241, 1210, 1145, 1078, 1044, 1001, 729; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.32 (d, *J* = 2.0 Hz, 1H, H-5), 6.30 (dd, *J* = 3.2, 1.9 Hz, 1H, H-4), 6.09 (d, *J* = 3.1 Hz, 1H, H-3), 3.83 (t, *J* = 6.5 Hz, 2H, H-6), 2.87 (t, *J* = 6.5 Hz, 2H, H-7), 2.77 – 2.65 (brs, 1H, H-8); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 152.9 (C-2), 141.4(C-5), 110.3 (C-4), 106.4 (C-3), 60.8 (C-7), 31.5 (C-6).



(107)

As a yellow oil **R_f** (hexane:EtOAe 7:3): 0.53; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.35 (d, *J* = 2.3 Hz, 1H, H-5), 6.35 (dd, *J* = 3.2, 2.0 Hz, 1H, H-4), 6.21 (d, *J* = 3.2 Hz, 1H, H-3), 4.87 (q, *J* = 6.32 Hz, 1H, H6) , 1.53 (d, *J* = 6.7 Hz, 3H, H7); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 157.6 (C-2), 141.79 (C-5), 110.1 (C-4), 105.0 (C-3), 63.4 (C-6), 21.3 (C-7).

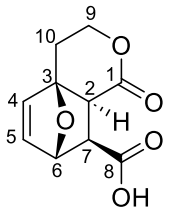
Synthesis of (4aR,7S,8R)-1-oxo-1,3,4,7,8,8a-hexahydro-4a,7 epoxyisochromene -8-carboxylic acid **(112)**



(105) **(111)** **(112)**

Maleic anhydride **(111)** (0.9 g, 8.92 mmol) was dissolved in toluene (15 mL). To this was added 2-(furan-2-yl)ethan-1-ol **(105)** (1 g, 8.92 mmol). The reaction mixture was stirred for 8

h at 80 °C, then was cooled at room temperature, filtered and washed with cold ether (10 mL) to afford a white solid **(112)** (1.5 g, 81%).

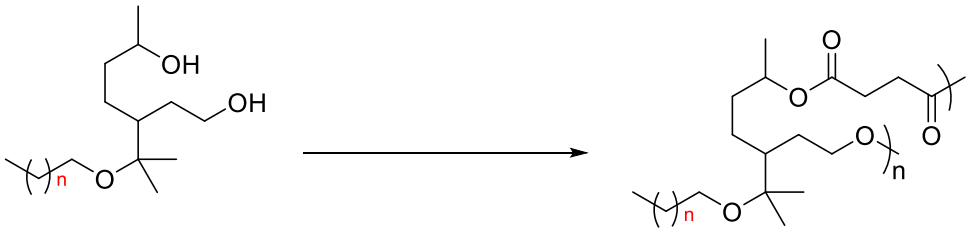


(112)

As a white solid compound; $\mathbf{R_f}$ (pentane:EtOAe 1:1): 0.27; **IR** (KBr, cm^{-1}) 2986, 2942, 2910, 1710, 1340; **^{1}H NMR** (400 MHz, DMSO) δ 12.36 (s, 1H, H-8), 6.51 – 6.41 (m, 2H, H-4 and H-5), 5.04 (d, *J* = 1.7 Hz, 1H, H-6), 4.44 – 4.31 (m, 2H, H-9), 2.92 – 2.73 (m, 2H, H-2, H-7), 2.59 – 2.52 (m, *J* = 1.9 Hz, 1H, H-10), 2.19 (dt, *J* = 14.8, 2.8 Hz, 1H, H-10); **^{13}C NMR** (101 MHz, DMSO) δ 173.4 (C-8), 170.6 (C-1), 139.3 (C-5), 136.8 (C-4), 85.8 (C-3), 81.6 (C-6), 65.4 (C-9), 48.1(C-2), 47.1 (C-7), 26.1 (C-10); **HRMS** (ESI, $[C_{10}H_{10}O_5+H]^+$): measured 211.0611, theoretical 211.0601.

6.4 Synthesis of Chapter Four:

Polycondensation

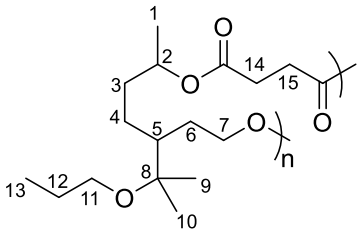


n = 1 **(77)**
n = 6 **(78)**

Method **A**: **77** (0.30 g, 1.23 mmol) was dissolved in dry dichloromethane (1 mL) and cooled to 0 °C pyridine (0.71 mL, 8.8 mmol) was added dropwise over 5 minutes. Succinyl chloride (0.51 mL, 6.45 mmol) was dissolved in dry dichloromethane (1.5 mL) and added dropwise over 20

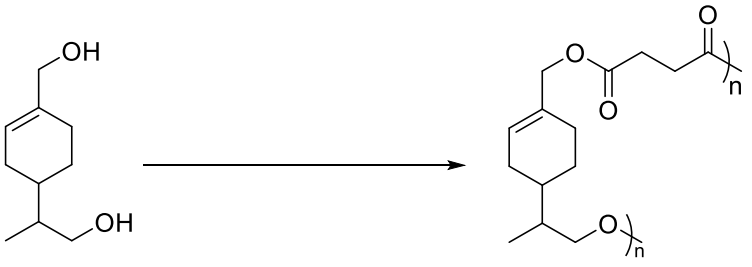
minutes, and the resulting solution was then stirred at room temperature (96 h). The polymer was then isolated by precipitation in excess of EtOAc to yield a pale yellow.

Method **B**: All reagents were dried under vacuum at 25 ℃ for at least 24 h prior to use. The **(77)** (0.22 g, 0.95 mmol) was added to a 25 mL round-bottomed flask equipped with a condenser, and the trap cooled to 0 ℃ succinic acid **(114)** (0.123 g, 1.05 mmol) was added, and the reaction heated to 120 ℃ (2h). The metal catalyst ($Sn(oct)_2$) was added (1 mol%), the temperature increased to 150 ℃ and the system put under vacuum. After an elapsed time, the polymerisation was stopped by cooling to 0 ℃ and the polymer washed with MeOH.



(115)

^{1}H NMR (400 MHz, $CDCl_3$) δ 4.93 – 4.69 (m, 1H), 4.21 – 3.89 (m, 1H), 3.51 (s, 2H), 3.43 – 3.21 (m, 2H), 2.78 – 2.46 (m, 4H), 1.81 – 1.16 (m, 14H), 1.14 – 0.76 (m, 6H), **IR** (KBr, cm^{-1}) 2961, 2931, 2873, 1728, 1682, 1418, 1377, 1305, 1196, 1162, 993, 891, 636.

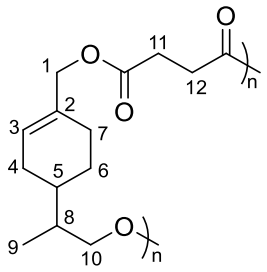


(89) **(118)**

Method **A**: **89** (0.300 g, 1.76 mmol) was dissolved in dry dichloromethane (1 mL) and cooled to 0 ℃ pyridine (0.71 mL, 8.8 mmol) was added dropwise over 5 minutes. Succinyl chloride

(0.21 mL, 1.94 mmol) was dissolved in dry dichloromethane (1.3 mL) and added dropwise over 15 minutes, the resulting solution was then stirred at room temperature for 72 h. The polymer was then isolated by precipitation in an excess of EtOAc to yield a pale yellow, viscous oil.

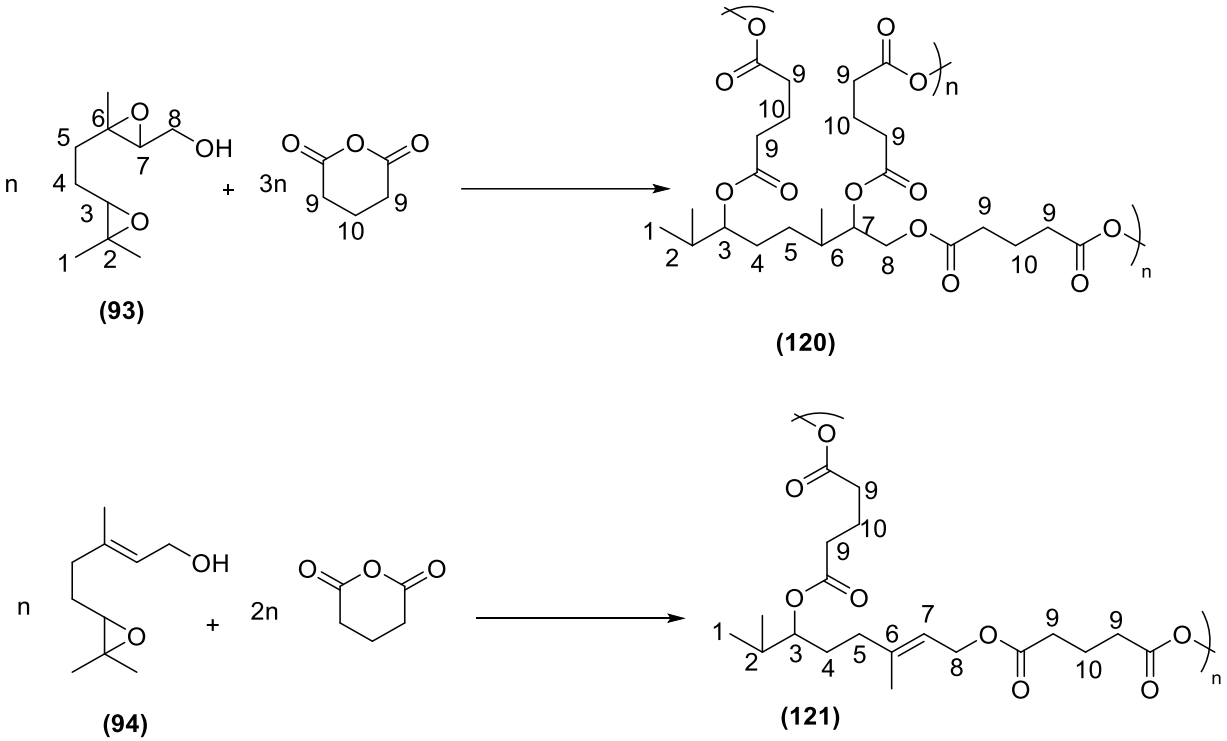
Method **B**: All reagents were dried under vacuum at 25 ℃ for at least 24 h before use. The **(89)** (0.300 g, 1.76 mmol) was added to a 25 mL round-bottomed flask equipped with a condenser and trap cooled to 0 ℃, succinic acid **(114)** (0.23 g, 1.94 mmol) was added, and the reaction heated to 120 ℃ (2 h). The metal catalyst ($Sn(oct)_2$) was added (1 mol%), the temperature increased to 150 ℃, and the system was put under vacuum. After an elapsed time, the polymerisation was stopped by cooling to 0 ℃, and the polymer was washed with MeOH.



(118)

^{1}H NMR (400 MHz, DMSO) δ 5.66 (br, 1H, H-3), 4.38 (br, 2H, H-1), 3.88 – 3.77 (m, 2H, H-10), 2.54 (s, 4H, H-11 and H-12), 1.98 – 1.93 (m, 2H), 1.80 – 1.54 (m, 8H), 1.24 – 1.05 (m, 3H), **IR** (KBr, cm^{-1}), 2923, 1727, 1150, 994.

Ring Opening Polymerisation



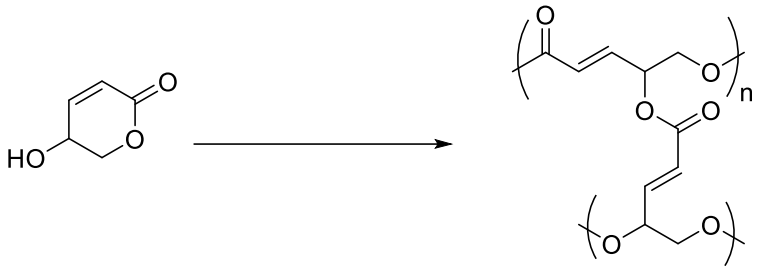
(93) (1 g, 5.37 mmol) was added to a 50 mL round-bottomed flask and dried under vacuum for 3 hours. Toluene (6 mL), glutaric anhydride (1.23 g, 10.74 mmol), and $La(oTf)_3$ (0.032 g, 0.54 mmol) were added under a flow of N_2. The reaction mixture was stirred and heated at 80 °C for 72 h. After an elapsed time, the polymerisation was stopped by cooling to 0 °C, and the polymer was washed with MeOH.

(Table 4.3, entry 3); **^{1}H NMR** (400 MHz, $CDCl_3$); δ 4.13 (m, 12H, H-9), 3.2 (br, 2H, H-8), 2.9 (m, 2H, H-3, H-7), 2.1 (m, 6H, H-10), 1.53 (br, 4H, H-4, H-5). **IR** (KBr, cm^{-1}) 2939, 1704, 1408, 1149.

(94) (0.3 g, 1.76 mmol) was added to a 50 mL round-bottomed flask and dried under vacuum for 2 hours. THF (4 mL), glutaric anhydride (0.20 g, 1.76 mmol), and $La(oTf)_3$ (0.01 g, 0.017 mmol) were added under a flow of N_2. The reaction mixture was stirred and heated at 60 °C

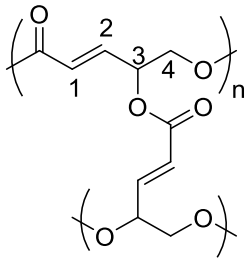
for 120 h. After an elapsed time, the polymerisation was stopped by cooling to 0 ℃, and the polymer was washed with MeOH.

(Table 4.3, entry 6); **^{1}H NMR** (400 MHz, $CDCl_3$); δ 5.8 (dd, 2H, H-7), 3.2 (br, 2H, H-8), 2.9 (m, 8H, H-9), 2.5 (m, 1H, H-3), 2.3 (br, 2H, H-5) 1.9 (m, 4H, H-10), 1.7 (m, 2H, H-4), 1.56 (m, 6H, H-1). **IR** (KBr, cm^{-1}) 2952, 2923, 1731, 1447, 1417, 1375, 1317, 1200, 1165, 1060, 1032, 991.



(102) **(122)**

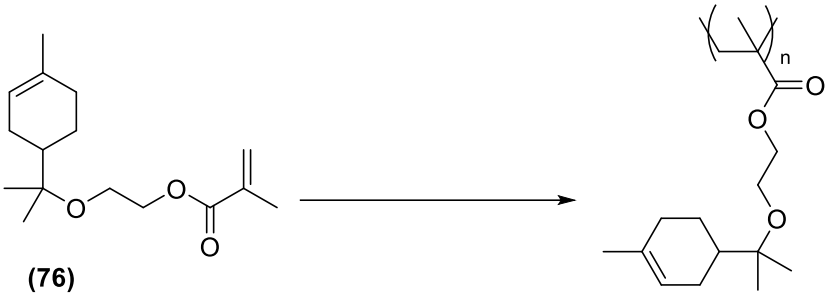
102 (0.6 g, 5.26 mmol) was added to a 50 mL round-bottom flask and dried under vacuum for 1 h. It was then flushed with N_2 and heated at 100 C for 24 h.



(122)

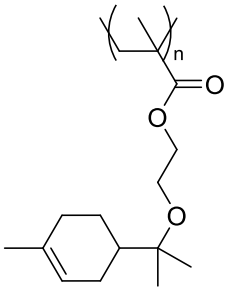
^{1}H NMR (400 MHz, $CDCl_3$); δ 7.38 –7.51 (dd, 1H, H-1), 6.20 – 6.36 (dd, 1H, H-2), 4.31 – 4.54 (m, 1H, H-3), 2.50 – 3.20 (m, 2H, H-4). **IR** (KBr, cm^{-1}) 3401, 3104, 2929, 1714, 1621, 1584, 1563, 1541, 1400, 1243, 1196, 1122, 783.

Radical Polymerisation



(76) (123)

The reaction was carried out by mixing **104** (0.250 g) with toluene (0.5 mL) DDM (1% w/w) and AIBN (2% w/w) in a 15 mL vial. The mixture was previously degassed by freeze-pump-thaw technique and then heated up to 90 ℃ for 20 h.



(123)

^{1}H NMR (400 MHz, $CDCl_3$) δ 5.45 – 5.34 (m, 1H), 4.19 – 3.93 (m, 2H), 3.63 – 3.43 (m, 2H), 2.09 – 1.92 (m, 4H), 1.90 – 1.77 (m, 3H), 1.66 (s, 5H), 1.27 (s, 3H), 1.18 – 1.07 (m, 7H), **IR** (KBr, cm^{-1}) 2924, 1727, 1451, 1363, 1245, 1137, 999, 799, 730.

References:

1. X. Jiao, K. Zheng, Z. Hu, S. Zhu, Y. Sun and Y. Xie, *Adv Mater*, 2021, **33**, e2005192.
2. A. Paradowska-Stolarz, M. Wieckiewicz, A. Owczarek and J. Wezgowiec, *Int J Mol Sci*, 2021, **22**,10337.
3. H. Namazi, *Bioimpacts*, 2017, **7**, 73-74.
4. T. Yokozawa and A. Yokoyama, *Progress in Polymer Science*, 2007, **32**, 147-172.
5. K. Matyjaszewski and J. Spanswick, *Materials Today*, 2005, **8**, 26-33.
6. H. K. Lee, K. T. Bang, A. Hess, R. H. Grubbs and T. L. Choi, *J Am Chem Soc*, 2015, **137**, 9262-9265.
7. G. W. Coates, *Chem Rev*, 2000, **100**, 1223-1252.
8. L. K. Johnson, C. M. Killian and M. Brookhart, *J Am Chem Soc*, 1995, **117**, 6414-6415.
9. N. E. Kamber, W. Jeong, R. M. Waymouth, R. C. Pratt, B. G. Lohmeijer and J. L. Hedrick, *Chem Rev*, 2007, **107**, 5813-5840.
10. S. Kobayashi and A. Makino, *Chemical reviews*, 2009, **109**, 5288-5353.
11. T. F. De Greef, M. M. Smulders, M. Wolffs, A. P. Schenning, R. P. Sijbesma and E. W. Meijer, *Chem Rev*, 2009, **109**, 5687-5754.
12. S. R. Nicholson, N. A. Rorrer, A. C. Carpenter and G. T. Beckham, *Joule*, 2021, **5**, 673-686.

13. https://www.european-bioplastics.org/bioplastics/ and https://www.european-bioplastics.org/market/ and https://blogs.iadb.org/sostenibilidad/en/circular-economy-now-or-never/ accessed on 24 Oct 2023.

14. M. Bergmann, L. Gutow and M. Klages, *Marine anthropogenic litter*, Springer Nature, 2015, 185-200.

15. F. Lüdeke-Freund, S. Gold and N. M. P. Bocken, *Journal of Industrial Ecology*, 2018, **23**, 36-61.

16. U. De Corato, I. De Bari, E. Viola and M. Pugliese, *Renewable and Sustainable Energy Reviews*, 2018, **88**, 326-346.

17. Z. Wang, M. S. Ganewatta and C. Tang, *Progress in Polymer Science*, 2020, **101**, 101197.

18.https://espas.secure.europarl.europa.eu/orbis/system/files/generated/document/en/plastic.pdf accessed on 26 Oct 2023.

19. I. Cumpstey, *ISRN Org Chem*, 2013, **2013**, 417672.

20. C. Felgueiras, N. G. Azoia, C. Goncalves, M. Gama and F. Dourado, *Front Bioeng Biotechnol*, 2021, **9**, 608826.

21. L. García-Guzmán, G. Cabrera-Barjas, C. G. Soria-Hernández, J. Castaño, A. Y. Guadarrama-Lezama and S. Rodríguez Llamazares, *Polysaccharides*, 2022, **3**, 136-177.

22. G. L. Gregory, E. M. Lopez-Vidal and A. Buchard, *Chem Commun (Camb)*, 2017, **53**, 2198-2217.

23. J. R. G. Carvalho, G. Conde, M. L. Antonioli, C. H. Santana, T. O. Littiere, P. P. Dias, M. A. Chinelatto, P. A. Canola, F. J. Zara and G. C. Ferraz, *Molecules*, 2021, **26**, 1-15.

24. K. J. Jem and B. Tan, *Advanced Industrial and Engineering Polymer Research*, 2020, **3**, 60-70.

25. A. Naseem, S. Tabasum, K. M. Zia, M. Zuber, M. Ali and A. Noreen, *Int J Biol Macromol*, 2016, **93**, 296-313.

26. A. Gandini and T. M. Lacerda, *Molecules*, 2021, **27**, 1-26.

27. H. Luo, E. P. Weeda, M. Alherech, C. W. Anson, S. D. Karlen, Y. Cui, C. E. Foster and S. S. Stahl, *J Am Chem Soc*, 2021, **143**, 15462-15470.

28. M. Alherech, S. Omolabake, C. M. Holland, G. E. Klinger, E. L. Hegg and S. S. Stahl, *ACS Cent Sci*, 2021, **7**, 1831-1837.

29. F. S. Chakar and A. J. Ragauskas, *Industrial Crops and Products*, 2004, **20**, 131-141.

30. A. Gandini and M. Lacerda Talit, *Polymers from Plant Oils*, John Wiley & Sons, Inc, 2nd ed., 2019.

31. J. A. C. Silva, L. M. Grilo, A. Gandini and T. M. Lacerda, *Polymers (Basel)*, 2021, **13**, 1-24.

32. J. Zhang, J. Huang, G. Zhu, X. Yu, J. Cheng, Z. Liu, Y. Hu, Q. Shang, C. Liu, L. Hu and Y. Zhou, *Green Chemistry*, 2021, **23**, 5875-5886.

33. R. Wijayapala, S. Mishra, B. Elmore, C. Freeman and S. Kundu, *Journal of Applied Polymer Science*, 2019, **136**, 1-7.

34. I. V. Andreeva, D. H. Zaitsau, S. Qian, V. V. Turovtzev, A. A. Pimerzin, J. E. Bara and S. P. Verevkin, *Chem Eng Sci*, 2022, **247**, 117032.

35. M. Ripoll and L. Betancor, *Curr. Opin. Green Sustain. Chem*, 2021, **28**.

36. X. Luo, X. Ge, S. Cui and Y. Li, *Bioresour Technol*, 2016, **215**, 144-154.

37. N. Ebadipour, S. Paul, B. Katryniok and F. Dumeignil, *Catalysts*, 2020, **10**, 1021.

38. H. Zhang, H. Li, A. Wang, C. Xu and S. Yang, *Adv in Poly Tech*, 2020, 1-17.

39. K. Lang, S. Bhattacharya, Z. Ning, R. J. Sanchez-Leija, M. T. K. Bramson, R. Centore, D. T. Corr, R. J. Linhardt and R. A. Gross, *Biomacromolecules*, 2020, **21**, 3197-3206.

40. K. Pounds, S. Jairam, H. Bao, S. Meng, L. Zhang, S. A. Godinez, D. A. Savin, W. Pelletier, M. J. Correll and Z. Tong, *ACS Appl Mater Interfaces*, 2021, **13**, 23268-23281.

41. R. Coll, S. Udas and W. A. Jacoby, *Energy & Fuels*, 2001, **15**, 1166-1172.

42. M. S. Ganewatta, W. Ding, M. A. Rahman, L. Yuan, Z. Wang, N. Hamidi, M. L. Robertson and C. Tang, *Macromolecules*, 2016, **49**, 7155-7164.

43. M. George, P. G. Mussone and D. C. Bressler, *J Appl Polym Sci*, 2016, **133**.

44. A. Gandini and T. M. Lacerda, *Macromol. mater. eng.*, 2022, **307**.

45. X. Tong, Y. Ma and Y. Li, *App Cat A: General*, 2010, **385**, 1-13.

46. A. Gandini and M. N. Belgacem, *Prog. Polym. Sci.*, 1997, **22**, 1203-1379.

47. C. Moreau, M. N. Belgacem and A. Gandini, *Top. Catal.*, 2004, **27**, 11-30.

48. A. Gandini and N. Belgacem, 2008, Chapter 6, 115-152.

49. A. Gandini, *Polym. Chem.*, 2010, **1**, 245-251.

50. M. Decostanzi, R. Auvergne, B. Boutevin and S. Caillol, *Green Chem*, 2019, **21**, 724-747.

51. R. G. Dastidar, J. E. Chavarrio, Z. Jiang, D. J. McClelland, M. Mavrikakis, G. W. Huber, *Appl Cat B: Environ. Energ*, 2025, **360**, 124519.

52. S. Feng, M. Schmitt and E. Y. X. Chen, *Macromol Chem Phys*, 2015, **216**, 1421-1430.

53. E. Y. X. Chen, *Chem Rev*, 2009, **109**, 5157-5214.

54. S. Singhal, S. Agarwal, M. P. Mudoi, N. Singhal and R. Singh, *Biomass Convers Biorefin*, 2021, **13**, 15619-15636.

55. K. Ma, H. Jiang, G. Chen, W. Wang and Y. Zhang, *High Perform Polym*, 2021, **34**, 209-220.

56. A. Samir, F. H. Ashour, A. A. Abdel Hakim and M. Bassyouni, *npj Mater Degrad 6*, 2022, **68**, 1-28.

57. Y. Zhu, C. Romain and C. K. Williams, *Nature*, 2016, **540**, 354-362.

58. A. Rehman, E. Russell, F. Saleem, F. Javed, S. Ahmad, V. C. Eze and A. Harvey, *J. Environ. Chem. Eng.*, 2021, **9**, 104680.

59. W. Chen and A. M. Viljoen, *S. Afr. J. Bot.*, 2010, **76**, 643-651.

60. R. Ciriminna, M. Lomeli-Rodriguez, P. Demma Cara, J. A. Lopez-Sanchez and M. Pagliaro, *Chem Commun (Camb)*, 2014, **50**, 15288-15296.

61. K. A. Vespermann, B. N. Paulino, M. C. Barcelos, M. G. Pessoa, G. M. Pastore and G. Molina, *Appl Microbiol Biotechnol*, 2017, **101**, 1805-1817.

62. P. A. Wilbon, F. Chu and C. Tang, *Macromol Rapid Commun*, 2013, **34**, 8-37.

63. M. R. Thomsett, T. E. Storr, O. R. Monaghan, R. A. Stockman and S. M. Howdle, *Green Materials*, 2016, **4**, 115-134.

64. J. Zhao and H. Schlaad, in *Bio-synthetic Polymer Conjugates*, 2011, **166**, 151-190.

65. F. Della Monica and A. W. Kleij, *Polym Chem*, 2020, **11**, 5109-5127.

66. C. M. Byrne, S. D. Allen, E. B. Lobkovsky and G. W. Coates, *J. Am. Chem. Soc.*, 2004, **126**, 11404-11405.

67. M. M. Kleybolte and M. Winnacker, *Macromol Rapid Commun*. 2021, **42**, 2100065.

68. C. Li, R. J. Sablong, R. van Benthem and C. E. Koning, *ACS Macro Lett*, 2017, **6**, 684-688.

69. M. R. Thomsett, J. C. Moore, A. Buchard, R. A. Stockman and S. M. Howdle, *Green Chem*, 2019, **21**, 149-156.

70. D. Zhang, M. A. Hillmyer and W. B. Tolman, *Biomacromolecules*, 2005, **6**, 2091-2095.

71. M. Bähr, A. Bitto and R. Mülhaupt, *Green Chemi*, 2012, **14**.

72. M. M. Kleybolte, L. Zainer, J. Y. Liu, P. N. Stockmann and M. Winnacker, *Macromol Rapid Commun*, 2022, **43**, 2200185.

73. W. Mączka, K. Wińska and M. Grabarczyk, *Molecules*, 2020, **25**.

74. D. Haddleton, H. Liu and V. Maugein, *Polymer Chemistry*, 2024, **15**, 1-13.

75. A. Masyita, R. Mustika Sari, A. Dwi Astuti, B. Yasir, N. Rahma Rumata, T. B. Emran, F. Nainu and J. Simal-Gandara, *Food Chemistry,* 2022, **13**.

76. M. Firdaus, L. Montero de Espinosa and M. A. R. Meier, *Macromolecules*, 2011, **44**, 7253-7262.

77. A. Corma, S. Iborra and A. Velty, *Chem Rev*, 2007, **107**, 2411-2502.

78. V. D. Zeijden and C. Mattheis, *Synthesis*, 1996, 847-850.

79. D. C. Rosenfeld, S. Shekhar, A. Takemiya, M. Utsunomiya and J. F. Hartwig, *Org Lett*, 2006, **8**, 4179-4182.

80. J. Yadav, B. S. Reddy, G. Narasimhulu and K. Purnima, *Tetrahedron Letters*, **2009**, 50, 5783-5785.

81. M. R. Becker, J. P. Reid, K. A. Rykaczewski and C. S. Schindler, *ACS Catalysis*, 2020, **10**, 4387-4397.

82. F. Obermeier, D. Hense, P. N. Stockmann and O. I. Strube, *Green Chem*, 2024, **26**, 4387-4416.

83. W. K. Chan, W. Y. Yu, C. M. Che and M. K. Wong, *J Org Chem*, 2003, **68**, 6576-6582.

84. D. Yang and C. Zhang, *J Org Chem*, 2001, **66**, 4814-4818.

85. P. Spannring, P.C.A. Bruijnincx, Bert. M. Weckhuysen, and R.J.M. Klein Gebbink, *Catal Sci Technol*, 2014, **4**, 2182.

86. A. R. Hergueta, C. López, F. Fernández, O. Caamaño and J. M. Blanco, *Tetrahedron: Asymmetry*, 2003, **14**, 3773-3778.

87. D. García, M. Jaramillo, F. Bustamante, A. L. Villa and E. Alarcón, *Braz. J. Chem. Eng.*, 2020, **38**, 89-100.

88. M. F. Sainz, J. A. Souto, D. Regentova, M. K. G. Johansson, S. T. Timhagen, D. J. Irvine, P. Buijsen, C. E. Koning, R. A. Stockman and S. M. Howdle, *Polym Chem*, 2016, **7**, 2882-2887.

89. R. Laible, *Chem Rev*, 1958, **58**, 807-843.

90. G. A. Bailey and D. E. Fogg, *J Am Chem Soc*, 2015, **137**, 7318-7321.

91. P. Chen, Y. Zhou, Q. Li, Q. Xiao, Y. Lun, Y. Huang and G. Ye, *Polymer*, 2022, **255**, 125153.

92. X. Zhao, W. Huang, S. Lin, X. Chen, X. Guo, D. Zou, G. Ye, *ACS Omega*, 2021, **24**, 15608-15616.

93. S. K. Rajaraman and J. V. Crivello, *Designed Monomers and Polymers*, 1998, **1**, 77–8

94. K. Kaczanowska, B. Trzaskowski, A. Peszczyńska, A. Tracz, R. Gawin, T. K. Olszewski and K. Skowerski, *Chem Cat Chem*, 2020, **12**, 6366-6374.

95. R. N. Nair and T. D. Bannister, *J Org Chem*, 2014, **79**, 1467-1472.

96. Y. Watanabe, S. Laschat, M. Budde, O. Affolter, Y. Shimada and V. B. Urlacher, *Tetrahedron*, 2007, **63**, 9413-9422.

97. M. Vayer, S. Zhang, J. Moran and D. Lebœuf, ACS Catalysis, 2022, 12, 3309-3316.

98. R. M. Cravero, M. González-Sierra and G. R. Labadie, *Helv. Chim. Acta*, 2003, **86**, 2741-2753.

99. C. J. O'Brien and D. A. Nicewicz, *Synlett*, 2021, **32**, 814-816.

100. J. Einhorn, C. Einhorn, F. Ratajczak and J.-L. Pierre, *J Org Chem*, 1996, **61**, 7452-7454.

101. H. B. Dong, M. Y. Yang, J. Z. Jiang and M. A. Wang, *J Asian Nat Prod Res*, 2013, **15**, 880-884.

102. K. Yan, G. Wu, T. Lafleur and C. Jarvis, *Renew. Sustain. Energy Rev.*, 2014, **38**, 663-6

103. J. K. Raman and E. Gnansounou, *Bioresource Technology*, 2015, **185**, 202-210.

104. Y. Lee, E. E. Kwon and J. Lee, *Rev. Environ. Sci. Biotechnol.*, 2019, **18**, 317-334.

105. M. J. Taylor, L. J. Durndell, M. A. Isaacs, C. M. A. Parlett, K. Wilson, A. F. Lee and G. Kyriakou, *Appl. Catal. B.*, 2016, **180**, 580-585.

106. A. Mandalika, L. Qin, T. K. Sato and T. Runge, *Green Chem*, 2014, **16**, 2480-2489.

107. R. Mariscal, P. Maireles-Torres, M. Ojeda, I. Sádaba and M. López Granados, *Energy Environ. Sci.*, 2016, **9**, 1144-1189.

108. S. Chen, R. Wojcieszak, F. Dumeignil, E. Marceau and S. Royer, *Chem Rev*, 2018, **118**, 11023-11117.

109. J. Kaur, *Asian J Chem*, 2017, **29**, 2091-2094.

110. Z. Li and R. Tong, *J Org Chem*, **2016**, 81, 4847-4855.

111. G. Zhao and R. Tong, *Green Chem*, 2019, **21**, 64-68.

112. L. Brecker, M. F. Kögl, C. E. Tyl, R. Kratzer and B. Nidetzky, *Tetrahedron Lett*, 2006, **47**, 4045-4049.

113. A. Z. Aljahdali, S. A. Freedman, J. Scott, M. Li and G. A. O'Doherty, *Med Chem Comm*, 2019, **10**, 1205-1211.

114. M. P. Croatt and E. M. Carreira, *Org lett*, 2011, **13**, 1390-1393.

115. M. Dangalov, A. Fernández-Figueiras, M. A. Ravutsov, E. Vakarelska, M. K. Marinova, N. R. Candeias and S. P. Simeonov, *ACS cat*, 2023, **13**, 1916-1925.

116. H. Y. Wang, K. Yang, S. R. Bennett, S. r. Guo and W. Tang, *Angew. Chem. Int. Ed.*, 2015, **54**, 8756-8759.

117. M. Shan and G. A. O'Doherty, *Org lett*, 2010, **12**, 2986-2989.

118. C. Lemini, M. Ordo≁ ez, J. Perez-Flores and R. Cruz-Almanza, *Synth. Commun.*, 1995, **25**, 2695-2702.

119. J. Wenz, H. Wadepohl and L. H. Gade, *Chem Commun (Camb)*, 2017, **53**, 4308-4311.

120. S. Yakabe, *Synth. Commun.*, 2010, **40**, 1339-1344.

121. B. Alcaide, P. Areces, E. Borredon, C. Biurrun, J. Castells and J. Plumet, *Heterocycles*, 1990, **31**, 1997-2002.

122. J. P. Varghese, A. Sudalai and S. Iyer, *Synth. Commun.*, 1995, **25**, 2267-2273.

123. Z. Li, M. K. Gupta and T. S. Snowden, *Eur. J. Org. Chem.*, 2015, **2015**, 7009-7019.

124. A. Pelter and B. Singaram, *J. Chem. Soc., Perkin Trans. I*, 1983, 1383-1386.

125. C.E. Jr. Carraher, *Introduction to Polymer Chemistry*. CRC Press, 2017.

126. V. Gounden and M. Singh, *Gels*, 2024, **10**, 43.

127. T. Takata, and D. Aoki, *Polym J*, 2018, **50**, 127–147.

128. M. Wang, *Science Direct Topics*, 2019.

129. T. Yokozawa, and A. Yokoyama, *Prog Polym Sci*, 2007, **32**, 147–172.

130. S.V. Vinogradova, and V.A. Vasnev, *Russ Chem Rev*, 2004, **73**, 487–500.

131. T. Sang, C.J. Wallis, G. Hill and G.J.P. Britovsek, *Eur Polym J*, 2020, **136**, 109873.

132. J.H. Saunders, and F. Dobinson, Chapter 7 The Kinetics of Polycondensation Reactions, 1976, **15**, 473–581.

133. Y. Hu, W. Daoud, K. Cheuk, and C. Lin, , 2016, *Materials*, **9**, 133.

134. A. Tardy, J. Nicolas, D. Gigmes, C. Lefay, and Y. Guillaneuf, 2017, *Chem Rev*, **117**,1319–1406.

135. K. Parkatzidis, H.S. Wang, N.P. Truong, and A. Anastasaki, *Chem*, 2020, **6**, 1575-1588.

136. H.K. Chan, W.-Y. Yu, C.-M. Che, and M. Wong, J *Org Chem*, 2003, **68**, 6576–6582.

137. S. Ramasamy, K.S.V.L. Narasimhan, V. Geetha Saraswathy and S. Sankararaman, *J Org Chem*, 1996, **61**, 1877-1879.

138. A. Corma, M.T. Navarro, L. Nemeth, and M. Renz, *Chem Commun*, 2001, 21, 2190-2191.

139. B. Mekonnen Sanka, D. Mamo Tadesse, E. Teju Bedada, E. T. Mengesha and N. Babu G, *Bioorganic Chemistry*, 2022, **119**, 105568.