

OXIDATION OF PRIMARY ALCOHOLS TO ALDEHYDES AND ESTERS

BY

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A thesis submitted in partial fulfilment of the requirements for the degree of

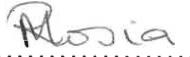
Master of Science (M.Sc.)

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August 1998

DECLARATION

I hereby certify that this research is the result of my own investigation which has not already been submitted in substance for any degree and is not being submitted in candidature for any other degree.

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I hereby certify that this statement is correct.

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CONTENTS

	Pages
ACKNOWLEDGEMENT	i
ABBREVIATIONS	ii
SUMMARY	iii
1. INTRODUCTION	1
1.1. THE FISCHER TROPSCH SYNTHESIS	1
1.1.1. Introduction	1
1.1.2. Catalysis	3
1.1.3. Processes	3
1.1.4. Industrial perspective	5
1.1.5. Products, separation and uses	6
1.1.6. Mechanism	7
1.1.7. Homologous alcohols	10
1.1.7.1. Introduction	10
1.1.7.2. Hydrocondensation of carbon monoxide	11
1.1.7.3. Mechanisms	12
1.2. PREPARATION OF ALDEHYDES FROM PRIMARY ALCOHOLS	14
1.2.1. Chromium (VI) Reagents	14
1.2.1.1. Chromium (VI) in acidic media	15
1.2.1.2. Chromium (VI) with heterocyclic bases	15
1.2.1.3. Other chromium (VI) reagents	17
1.2.2. Dimethyl sulfoxide reagents	18
1.2.3. Other oxidants	19
1.3. PREPARATION OF ESTERS FROM PRIMARY ALCOHOL	21
1.3.1. Esterification	21
1.3.1.1. Carboxylic acids and alcohols	21
1.3.1.2. Acylating agents and alcohols	22

1.3.1.3.	Alkylation of carboxylate anions	23
1.3.2.	Alcoholysis Reactions	24
1.3.2.1.	Nitriles and alkoxyimines	24
1.3.2.2.	Ortho esters	24
1.4.	SUPPORTED REAGENTS	25
1.4.1.	Introduction	25
1.4.2.	Types of Support Used	27
1.4.2.1.	Alumina	27
1.4.2.2.	Silica	27
1.4.2.3.	Other supports	28
1.5.	APPLICATIONS AND USES OF ALDEHYDES, ESTERS AND THEIR PRODUCTS	29
2.	DISCUSSION	33
2.1.	INTRODUCTION	33
2.2.	SYNTHESIS	34
2.2.1.	Oxidation of Alcohols to Aldehydes using Pyridinium Chlorochromate	34
2.2.2.	Oxidation of Alcohols to Aldehydes using Silica Gel-supported Pyridinium Chromate	37
2.2.3.	Oxidation of Alcohols to Aldehydes using Poly[vinyl(pyridinium chlorochromate)]	40
2.2.4.	Oxidation of Alcohols to Aldehydes and Esters using Silica Gel supported Chromium Trioxide	42
2.2.5.	Oxidation of Alcohols to Aldehydes and Esters using Chromium Trioxide	46
2.2.6.	Oxidation of Alcohols to Aldehydes and Esters using Alumina supported Chromium Trioxide	48
2.2.7.	Oxidation of Alcohols to Esters using Kieselguhr-supported Chromic Acid	52
2.2.8.	Oxidation of Alcohols to Esters using Aluminium Silicate-supported Chromic Acid	55

2.2.9.	Oxidation of Alcohols to Esters using Alumina-supported Pyridinium Chlorochromate	58
2.3.	CONCLUSION AND FUTURE PROPOSALS	62
2.3.1.	Comparison of the Oxidation Systems Used	62
3.	EXPERIMENTAL	67
3.1.	Instrumentation and General Procedures	67
3.2.	SYNTHESIS	68
3.2.1.	Oxidation of Alcohols to Aldehydes using Pyridinium Chlorochromate	68
3.2.2.	Oxidation of Alcohols to Aldehydes using Silica Gel-supported Pyridinium Chromate	72
3.2.3.	Oxidation of Alcohols to Aldehydes using Poly[vinyl (pyridinium chlorochromate)]	76
3.2.4.	Oxidation of Alcohols to Aldehydes and Esters using Silica Gel-supported Chromium Trioxide	78
3.2.5.	Oxidation of Alcohols to Aldehydes and Esters using Chromium Trioxide	86
3.2.6.	Oxidation of Alcohols to Aldehydes and Esters using Alumina supported Chromium Trioxide	91
3.2.7.	Oxidation of Alcohols to Esters using Kieselguhr-supported Chromic Acid	97
3.2.8.	Oxidation of Alcohols to Esters using Aluminium Silicate-supported Chromic Acid	102
3.2.9.	Oxidation of Alcohols to Esters using Alumina-supported Pyridinium Chlorochromate	107
4.	REFERENCES	112
5.	APPENDIX	117
	¹ H and ¹³ C NMR spectra	

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ABBREVIATIONS

SYMBOL	DEFINITION
R	Alkyl group
b.p.	Boiling point
m ³	cubic meter
d	doublet
E I	Electron ionisation
GC-MS	Gas chromatography mass spectrometry
g	grams
h	hours
M	metal
m	meter
ml	milliliter
min.	minutes
mol (mmol)	moles (millimoles)
m	multiplet
N	normal
NMR	Nuclear magnetic resonance
pbw	parts by weight
Py	pyridine
q	quartet
s	singlet
TMS	tertamethylsilane
t	triplet

SUMMARY

The initial aim of this research project was to oxidise C₂-C₄ alcohols to their respective aldehydes. However, isolation of these aldehydes was impossible due to their low boiling points. Another problem was the proximity of the boiling points of these aldehydes with the boiling points of solvents used in reactions. As a result, the alcohols investigated in this project were changed to C₄-C₆ alcohols.

Different oxidising reagents are known that oxidise primary alcohols to aldehydes. Of these, chromium (VI) has been used the most. In this project, Chromium (VI) supported on different inert inorganic supports was chosen as the oxidising reagent. The first task was therefore to synthesise these supported oxidants. The synthesis of some of these oxidants was lengthy. This is an advantage of the preparation of supported oxidants. Unsupported oxidants like PCC and chromium trioxide were only used as a basis of comparison to emphasise the usefulness of supported oxidants.

Pyridinium chlorochromate was used to oxidise primary alcohols to aldehydes in moderate yields. The reaction was found to be moisture sensitive. The yield and the duration of the reaction was found to be better with the use of molecular sieves. Silica gel-supported pyridinium chromate was also used to oxidise alcohols to aldehydes in good yields. Poly[vinyl(pyridinium chlorochromate)] was used to oxidise 1-hexanol and 1-pentanol to their respective aldehydes also in good yields. The duration of these reactions ranged from 30 min. to 3 days.

During the oxidation of alcohols using silica gel-supported chromium trioxide and diethyl ether/chromium trioxide it was found that the reaction conditions can be changed so that either aldehydes or symmetrical esters were the products. This was achieved by varying the duration of the reaction. Silica gel-supported chromium trioxide resulted in both the aldehydes and esters in good yields while the diethyl

Aluminium-supported chromium trioxide, kieselguhr-supported chromic acid, aluminium silicate-supported chromic acid and alumina-supported pyridinium chlorochromate were used to oxidise primary alcohols to symmetrical and unsymmetrical esters in good to excellent yields. The duration of these reactions varied from 1 hour to 48 hours depending on the conditions employed and the chain length of the reagents.

1. INTRODUCTION

1.1. THE FISCHER TROPSCH SYNTHESIS

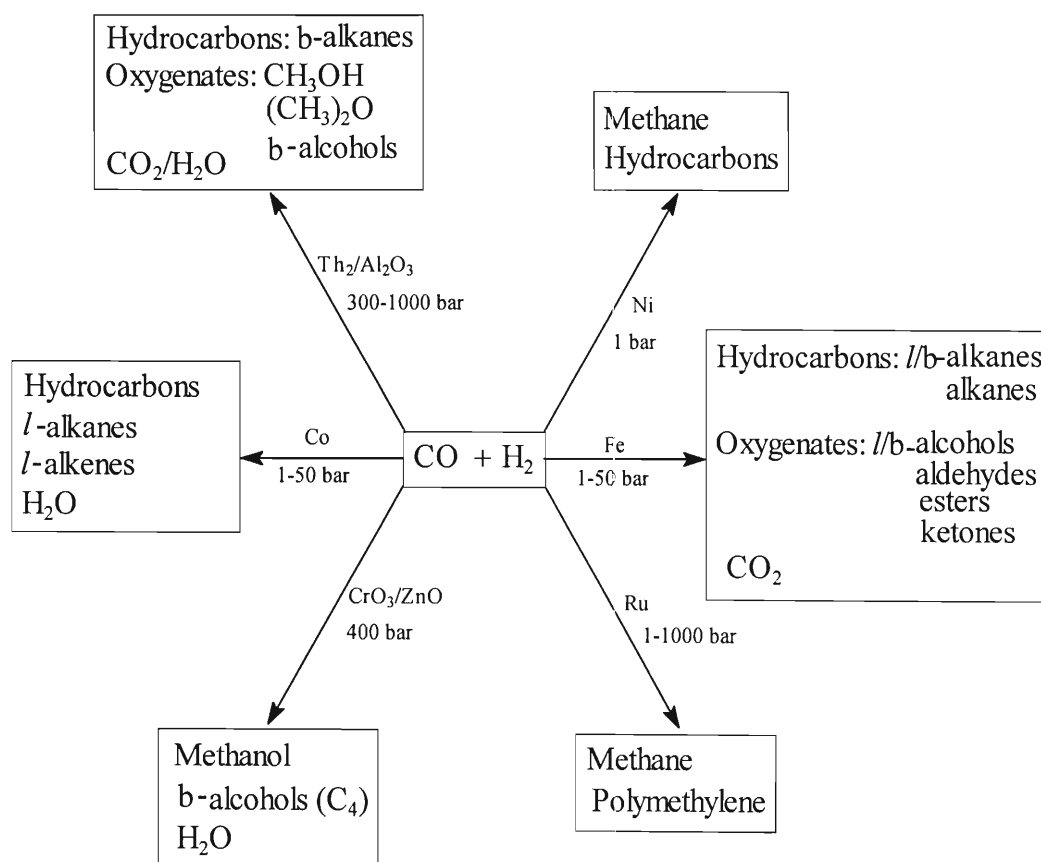
1.1.1. Introduction

The preparation of liquid hydrocarbons by the hydrogenation of carbon monoxide on cobalt-based contact masses, under rather severe conditions (100 bar/300-400°C), was first reported in 1916 by Badische Anilin and Soda Fabrik.¹ In 1925, as a result of systematic studies carried out at the Kaiser Wilhelm Institut für Kohleforschung, at Mühlheim/Ruhr, Fischer and Tropsch found that liquid hydrocarbons could be obtained at normal pressures (1 bar) by the interaction of CO/H₂ on certain iron and cobalt catalysts (250-300°C). This synthesis, subsequently known as the Fischer-Tropsch (F.T.) synthesis, aroused great industrial interest since it constituted an attractive alternative to the production of liquid hydrocarbons (fuel) from coal.¹

Germany has no significant indigenous petroleum sources. Just before World War II, nine plants had been built to convert synthesis gas from coal to liquid fuels with a total rated output of about 740 000 tons per year. The shortage of cobalt during the war prompted renewed interest in the iron catalysts and Ruhrchemie-Lurgi developed a medium-pressure industrial process based on iron catalysts.^{2,3} The abundance and low cost of petroleum, petroleum-derived olefins and hydrocarbon fuels in the 1950's and the 1960's led to the closure in most countries of these coal-based F. T. synthesis units.¹ South Africa has large coal reserves but essentially no petroleum. In 1955, a chemical plant in South Africa, Sasolburg, known as Sasol, became operational and continues to produce gasoline, waxes, and oxygenated aliphatic compounds.⁴

In the late 1970's, when petroleum feedstocks became especially costly, there was renewed interest in the F. T. synthesis. The catalytic conversion of CO and H₂ to hydrocarbons and oxygenated compounds, once again became an economically feasible route for the production of petrochemicals.⁵

The products obtained under the usual F.T. synthesis conditions consist of a complex mixtures of the following general types of hydrocarbons and oxygenated products: linear and methyl-branched alkanes together with cycloalkanes; linear terminal olefins accompanied by small amounts of *cis/trans* internal olefins; aromatic hydrocarbons, benzene, toluene, ethylbenzene and methylenes; linear alcohols, aldehydes, ketones, esters, and acids,^{1,6,7,8} CO is usually the side product (Scheme 1).^{6,9,10}



l, linear; *b*, branched

Scheme 1 Hydrocondensation of CO on different contact masses

1.1.2. Catalysts

The first catalysts used in the German normal and medium pressure F.T. synthesis units were all derived from cobalt supported on kieselguhr. The original Co/ThO₂/Cu/kieselguhr catalysts were replaced by 100 pbw Co/15 pbw ThO₂/200 pbw kieselguhr, then by standard catalysts 100 pbw Co/8 pbw MgO/5 pbw ThO/200 pbw kieselguhr, all this with the objective of increasing the degree of hydrocondensation.^{1-3,6,11}

There are only four metals which catalyse the hydrocondensation of carbon monoxide: these are iron, cobalt, nickel and ruthenium, nickel being somewhat less efficient than the other three (Scheme 1). A number of oxides are also known to show a significant activity in the F. T. synthesis, an example being thoria (ThO₂). Ruthenium is the only one of the four metals which is used in the pure state, *i.e.* unpromoted and unsupported. Iron requires promotion but not supporting, while cobalt and nickel are usually used with both promoters and support.⁴

The activities and selectivities of the cobalt and the iron catalysts differ to some extent. Cobalt catalysts give predominantly linear olefins and paraffins. Iron catalysts yield in addition some alcohols, ketones and other oxygenated compounds. Thus the iron catalysts tend to be more active, more robust and to have longer active lifetimes. It must be stressed that the performance of a given catalyst (selectivity, conversion) in the production is dependent upon both the conditions in the reactor (temperature, pressure, flow rate *etc.*) and upon the design of the reactor (fixed bed, fluidized bed *etc.*).¹

1.1.3. Processes

The scale up of laboratory experiments on the hydrocondensation of CO to industrial production units represent a major technical breakthrough; the major problems which had to be solved include the following:^{2,3,6,11-14}

- The dissipation of the heat occasioned by the exothermicity of the reaction, *i.e.* design of sequential reactors, cooled reactors and/or gas-recycle reactors.
- Steering the reaction, by an adequate control of feedstock composition, gas-recycle, residence time, *etc.*, towards the desired range of hydrocarbon products, *i.e.* design of flexible reactors.
- Prolonging the life of the catalyst by increasing its mechanical strength and by developing techniques permitting the periodic removal of accumulated hydrocarbon deposits.
- Developing adequate product separation processes.
- Recycling of the catalyst.

The solution proposed for overcoming the problem of exothermicity of the F.T. synthesis include sequential water-cooled fixed-bed reactors, entrained fluid-bed reactors, fluidised reactors, and liquid phase reactors.^{1,2,3,6,11-16} The first industrial normal-pressure units employed multiple-stage, water cooled, fixed-bed lamellar reactors. The gas loading and the conversion were controlled in the first reactor and the off-gas, after condensation of the products, was fed into a second reactor. No gas recirculation was employed and the final off-gas was used as a fuel source. Problems were encountered at the levels of the filling, the cleaning and the removal of the catalyst. Catalyst life was 3-6 months. The double-tube water-cooled pressure reactors used in the medium pressure F. T. units introduced several improvements. These reactors function under pressure of 7-12 bar with similar gas loadings as normal pressure units. The result was that more liquid products were present in the reactor thus ensuring a better heat elimination and catalyst washing. The use of up to three consecutive reactors with a gas recycle in the first reactor extended the catalyst lifetime to up to 12 months operation. These reactors operate at 20-25 bar/220-250°C with a fresh-gas loading of 500-600 m³/m³/h, a hot gas recycle and conversion of 65-70%; five such reactors each with 40 m³ catalyst permit a daily production of 250 tons of primary C₂ products.^{1,2}

In addition to the reactors mentioned above, entrained bed reactors have also been used in the synthesis of hydrocarbons: the purified CO/H₂ is passed under pressure through the

catalyst at 315-340°C and then into a settling reactor. The catalyst passes continuously between hot reaction and cooling zones and an intermediate settling chamber separates hot gases and the catalyst: the hot gases are cooled to condense the products (hydrocarbons, H₂O and oxygenates). The final gas may be recycled to the reactor either directly or via a gas reforming units; alternatively it can be used as a fuel.^{2,6,13,16}

1.1.4. Industrial Perspective

The C₂ and to a lesser extent the C₃ and C₄ products are predominant in the overall product distribution with both iron and cobalt F. T. catalysts; thus the C₂ hydrocarbons are minor products, whilst ethanol is a major component amongst the alcohols.^{1,17-19} Major current industrial objectives include selective CO hydrocondensation syntheses aimed at C₂-C₄ olefins as well as medium-chain olefins suitable for the oxo syntheses of plasticisers (C₆-C₁₂) and detergents (C₁₂-C₁₈).¹

The selectivity of iron-based catalysts can be altered by employing structural and/or chemical promoters. Structural promoters, usually difficult to reduce metal oxides which increase the active surface area, impede recrystallisation and impart added mechanical robustness to the contact masses.^{1,2,3,6} On the other hand, chemical promoters, which include copper and alkali or alkaline earth metals, modify the activity and selectivity of the catalyst.

Alkali additives (K₂CO₃) have a marked beneficial effect upon the activity and the selectivity of the catalyst, whilst the addition of copper greatly facilitates the activation of the original iron contact mass.^{6,20} The presence of alkali metal oxides tend to alter the product spectrum towards medium and long chain products. They also increase the olefin content of the hydrocarbons as well as the alcohol content of the product.^{6,11-13,21}

1.1.5. Products, Separation and Uses

The rich variety of products which may be obtained in the F. T. synthesis imparts a certain specificity to the product isolation techniques associated with each type of process. With cobalt catalyst the products are essentially water and hydrocarbons, whilst with iron contact masses oxygenated compounds are also formed. The repartition of these in the gaseous, hydrocarbon and aqueous phases complicates not only the analysis of the total product but also their separation.¹

The early F. T. syntheses produced liquid fuels and the conditions were set to give long-chain hydrocarbons and waxes.^{2,11} The gases leaving the reactor were cooled to condense out and separate the water and hydrocarbon layers; the uncondensed gases were scrubbed with water to remove acids and alcohols and the remainder either converted to CO, recycled or used as fuels.¹

The hydrocarbon condensate was separated by distillation. The volatile C₃-C₄ fraction was used as liquid gas or, if the olefin was sufficiently unsaturated, processed, *e.g.* by polymerisation to polymer petrol or carbonylation to oxo products. The C₅-C₁₀ fraction, b.p. 40-80°C, after alkali washing to remove acid impurities, constitutes the basis for synthetic motor petrol with a low octane number. The C₁₁-C₂₀ fraction, b.p. 180-320°C, formed the basis of a diesel fuel with a good cetane number (70-100). This fraction was also transformed into lubricating oils, detergents, plasticisers, *etc.* The paraffins boiling above 320°C were processed by vacuum and/or distillation techniques and separated into different types of waxes. The aqueous phase obtained with iron-based F. T. processes was subjected to distillation and certain alcohols (C₁-C₂) or alcohol mixtures (C₅) as well as ketones were separated.^{2,11}

The industrial units can thus be operated to give shorter-chain products containing a much higher proportion of olefins, in particular linear terminal olefins. F. T. products thus become not only a source of fuel but also of a potential source of α -olefins,

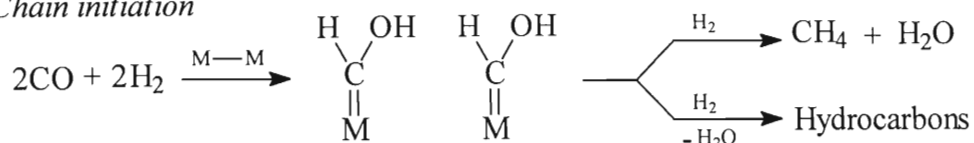
plasticiser alcohol (C₆-C₁₂), detergent alcohol (C₁₂ - C₁₈) and long-chain carboxylic acids, as well as lighter alcohols and ketones.¹

1.1.6. Mechanism

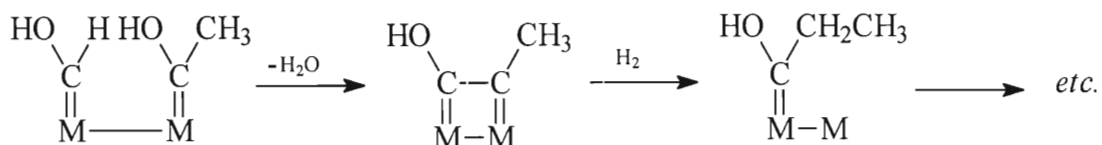
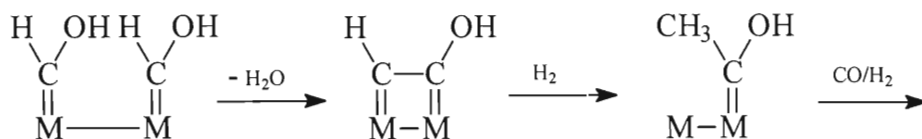
Over the years numerous attempts have been made to rationalise the formation of the various hydrocondensation products obtained by the interaction of CO and hydrogen on iron and cobalt contact masses.^{2,3,6,13,22-24} There is still some uncertainty concerning the primary reaction products in the F.T. synthesis and more particularly the sequence in which they are formed. Thus they could appear sequentially or they could be formed simultaneously from a common intermediate.^{17,25-29} In general, the hydrocondensation of CO involves the formation of C-C, C-H and C-O bonds and the elimination of the oxygen present originally in the CO.¹

Storch, Golumbic and Anderson^{3,6} proposed that the initial interaction of CO and H₂ on the catalytic surface led to oxygenated surface species. Chain growth was considered to proceed by intermolecular dehydration (scheme 2).

Chain initiation

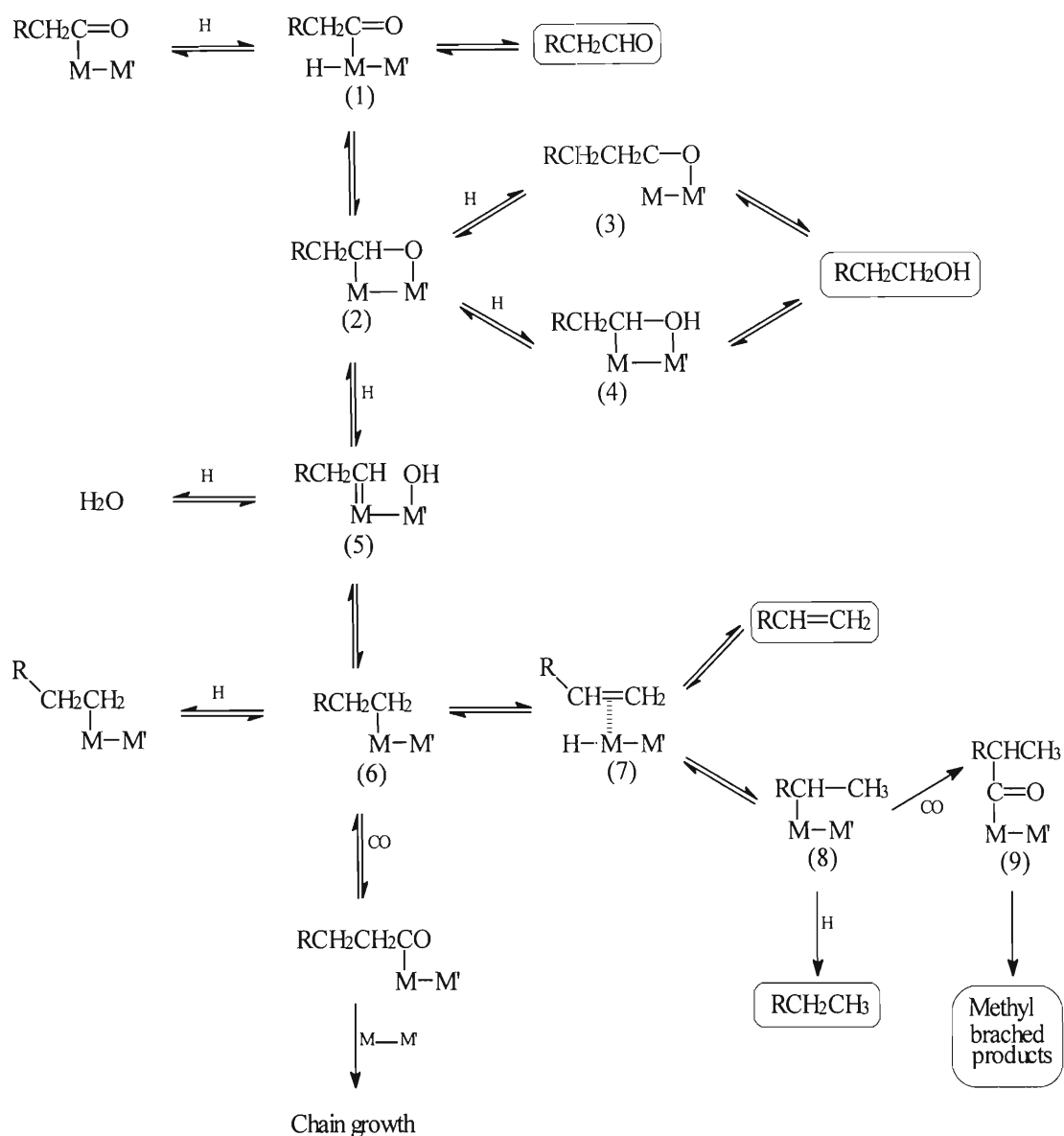


Chain growth, terminal carbon



Scheme 2

Product formation can be rationalised in terms of subsequent transformations of the acyl-metal species by stepwise H transfer reactions, as illustrated in scheme 3.²⁹ The hydridoacyl-metal intermediate (1) or the equivalent bidentate alkoxide (2) are the aldehyde precursors. The alcohols originate from the reduced form of (2), namely the alkoxide (3) or the hydroxyalkyl complex (4). The intermediate (2) can also evolve towards the metal carbene complex (5) and thence the alkyl-metal compound (6). The



Scheme 3

olefins are formed by β -metal hydride elimination in (6); the intermediate (*n*-olefin) metal hydride (7) permits the passage, *via* the isoalkyl and acyl complexes (8) and (9), from the linear to the branched products. The alkanes result from the hydrogenolysis of the alkyl-metal intermediate or by reductive elimination in the corresponding hydride. The alkyl-metal intermediates (6) and (8) ensure, by CO insertion, the chain propagation to homologous linear and branched products.

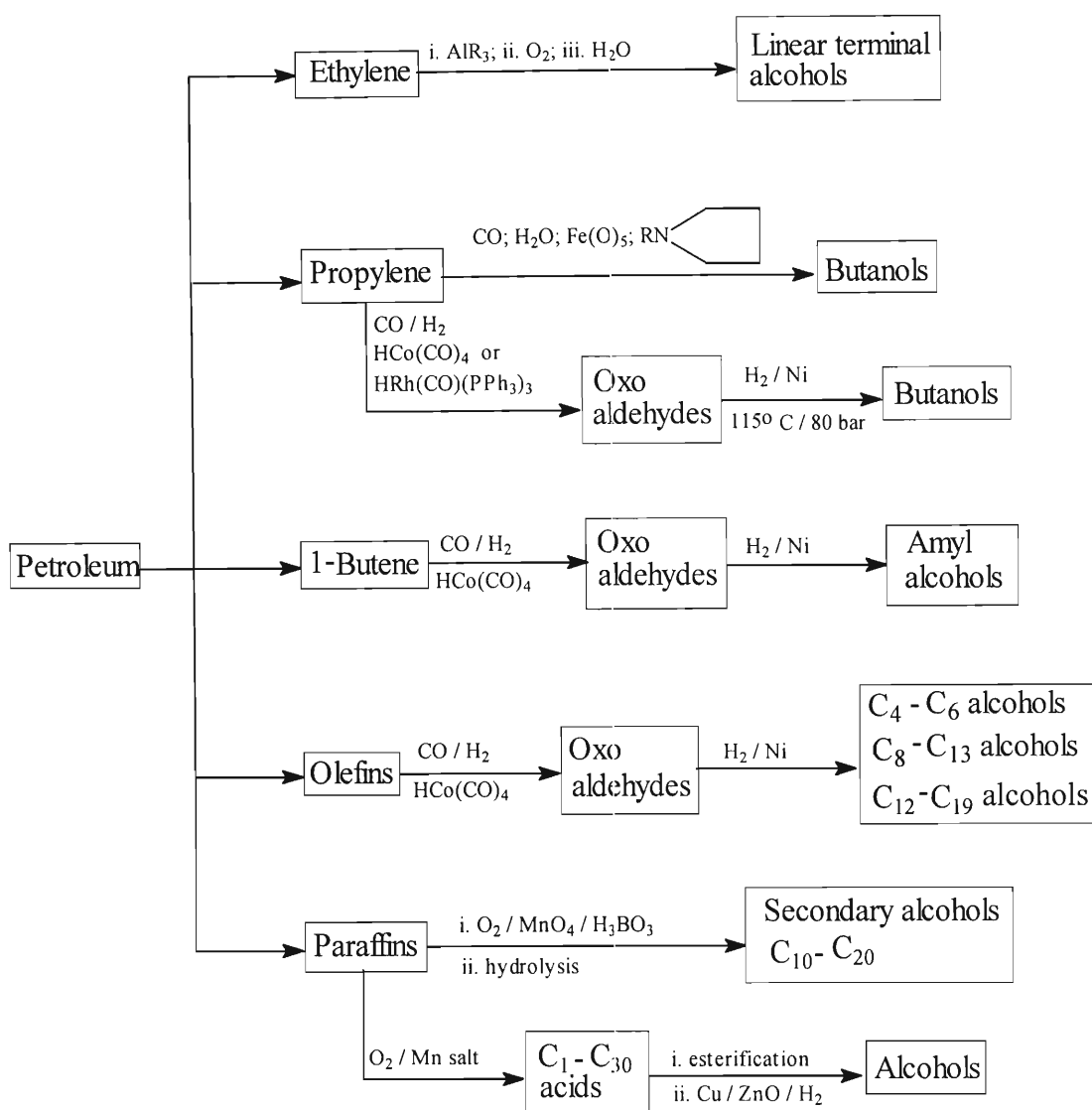
1.1.7. Homologous Alcohols

1.1.7.1. Introduction

Oxygenated compounds and specifically homologous alcohols are consistently formed as side products in the hydrocondensation and hydrogenation of CO on iron, cobalt, zinc and copper catalysts. The advent of petrochemistry with its relatively abundant supply of olefins and its new technologies, in particular the oxo synthesis, drastically reduced the economic impact of these coal-based syntheses of linear alcohols.¹

Many different syntheses of alcohols based upon hydrocarbon feedstock have been developed. These include hydroformylation of olefins followed by reduction of the resulting mixture of aldehydes, hydroxymethylation of olefins, oligomerization of ethylene with aluminium trialkyls, and subsequent oxidation and hydrolysis of the final mixture of trialkylaluminium compounds, and the controlled oxidation of hydrocarbons, either directly to a mixture of secondary alcohols or indirectly to carboxylic acid mixture followed by catalytic hydrogenation of the corresponding esters (scheme 4).¹

There are two main synthetic routes from coal to homologous alcohols in which CO represents the only source of carbon. The first is by the hydrocondensation of CO. The second originates in the methanol synthesis employing ZnO/Cr_2O_3 and ZnO/CuO catalysts and consists of the homologation of methanol.¹ Attention will be paid to the hydrocondensation of CO.



Scheme 4 Industrial syntheses of homologous alcohols.³⁰

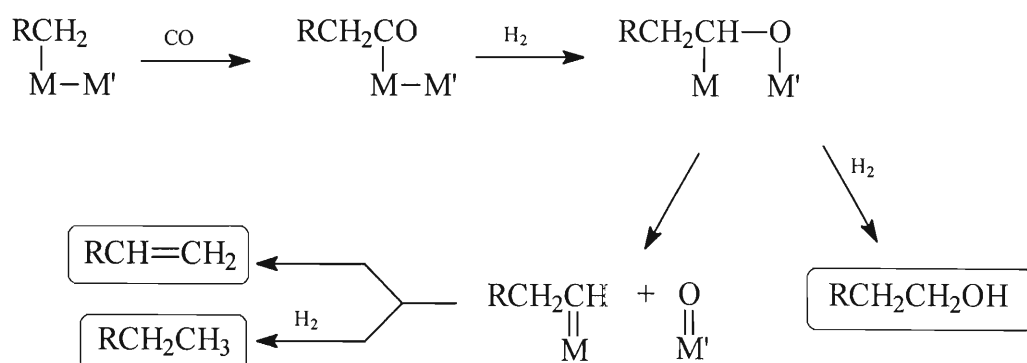
1.1.7.2. Hydrocondensation of Carbon Monoxide

The products formed in the hydrocondensation of CO can include homologous alkanes, alkenes, alcohols, aldehydes, ketones, acids and esters. The selectivity of a given catalyst and particularly of the iron-based contact masses towards hydrocarbons or oxygenated compounds depends upon numerous factors, including the catalyst preparation and pre-treatment, the operating conditions (temperature, pressure, conversion, gas composition, flow rate and recycle ratio) and the reactor design (fixed bed, fluidised or entrained bed). Thus, with iron contact masses, oxygenated products, particularly linear alcohols, are

favoured by certain adducts [alkali (K_2O), Ce and V], also by low temperature, high pressures, high space velocities, high recycle ratio and CO-rich feedstock. Furthermore, the types of homologous alcohols obtained depend upon the nature of the transition metal. Thus, in general terms, modified iron catalysts lead to mixtures of C_1 to C_{20} linear alcohols, often with a preponderance of ethanol. Modified cobalt catalysts give also essentially linear C_1 to C_{20} alcohols, but they are less active and tend to produce appreciable quantities of methanol and ethanol together with methane; modified zinc and copper catalysts lead to linear and branched alcohols containing appreciable quantities of isobutanol.¹

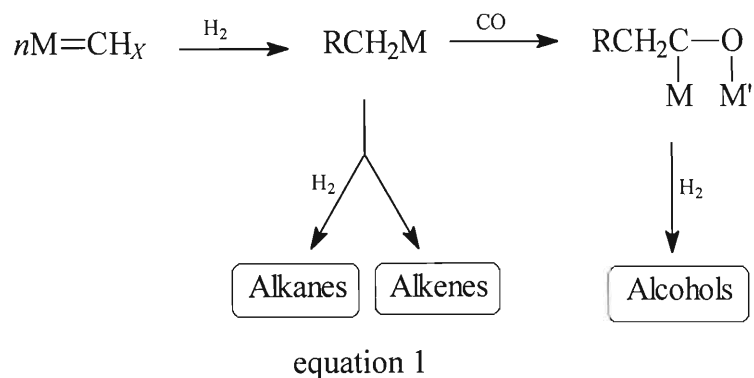
1.1.7.3. Mechanisms

The mechanisms of these homologous alcohol syntheses reflect the difference in reactivity associated with various transition metal centres. The hydrocondensation of CO on Fe and Co catalysts leads to mixtures of homologous alkanes, alkenes, alcohols and acids (esters). There is no clear evidence which indicates whether these products are formed simultaneously and independently or whether the oxygenated products (alcohols) are the initial products and the alkenes and alkanes are subsequent transformation products. Thus with a chain growth process based upon 'CO insertion' the alcohols could be transformed by the total hydrogenation of surface acyl species, without cleavage of the C-O bond. The alkanes and alkenes could be formed on the other hand by cleavage of the C-O bond and subsequent hydrogenation, as is depicted in Scheme 5.¹



Scheme 5 Syntheses of alcohols by CO insertion

Alternatively with a chain growth process based upon active carbon, carbyne or carbenoid intermediates the alcohols would be formed in a chain determination step as outlined in equation 1.



In conclusion, the overall industrial objectives in the area of CO hydrocondensation have shifted to finding alternative and selective syntheses of petroleum derived intermediates. Thus much current laboratory research is aimed at the preparation of new catalysts which would permit the direct, and selective transformation of CO/H₂ mixtures into light olefins (C₂-C₃), linear terminal olefins (C₆-C₂₀), light alcohols (C₁-C₄), oxygenated C₂ and C₃ compounds and eventually, from CO/H₂/NH₃, mixtures of amines and nitriles.

The aim of this section has been to show the extent of alcohol production in the F. T. syntheses. The main aim of this research project was to concentrate on the oxidation of primary alcohols to aldehydes and esters. The following sections summarise the various methods that have been employed for the oxidation of primary alcohols to aldehydes and esters.

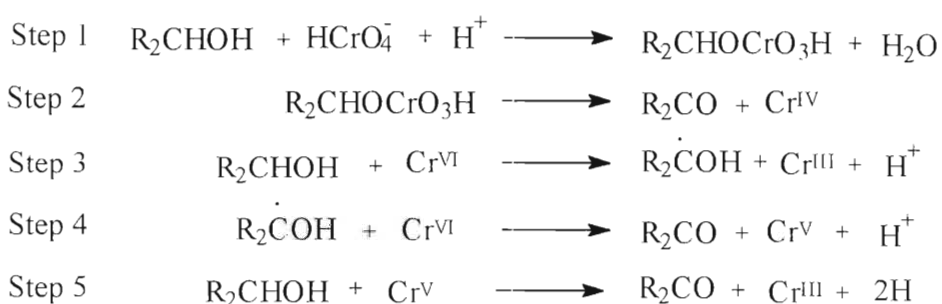
1.2. PREPARATION OF ALDEHYDES FROM PRIMARY ALCOHOLS

The oxidation of alcohols to carbonyl compounds is a fundamental reaction which is encountered at all levels of organic chemistry. As might be expected there are numerous methods and reagents which are available for carrying out this transformation. This section highlights some of the most commonly used reagents and methods for accomplishing this transformation.

1.2.1. Chromium (VI) Reagents

Chromium-based oxidants are probably the most widely used of all oxidising agents. They have been accepted readily by synthetic chemists since they are easy to handle and are readily available. However, they are not without their problems: work-up can be problematic, over-oxidation can occur and, at all times removal of the product from toxic chromium contaminants is a concern, especially with respect to large scale preparation.³¹

The mechanism of chromium (VI) oxidation of alcohols can be summarised as follows:³²



The following are a summary of the most common chromium (VI) reagents.

1.2.1.1. Chromium (VI) in acidic media

As can be expected, the oxidation of primary alcohols in acidic media is accompanied by the problem of over-oxidation to the carboxylic acid. Oxidation of primary alcohols with sodium dichromate in aqueous sulfuric acid does in fact afford the corresponding carboxylic acid.³³ Although replacing H₂SO₄ with acetic acid increases the solubility of organic substrates and the rate of oxidation, it is not suitable for the oxidation of primary alcohols to aldehydes since it too gives the carboxylic acid. Chromium (VI) oxide in DMF is a very poor oxidant but its reactivity can be catalysed by using concentrated sulfuric acid.³⁴ This reaction is considered mild and therefore acid sensitive functionalities are not affected. Similarly, sodium dichromate dihydrate in DMSO is a poor oxidant, but the addition of catalytic quantities of sulfuric acid affords the corresponding aldehydes in good yields.³⁵

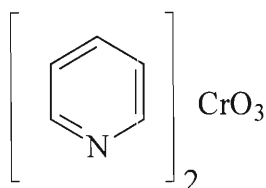
One of the best known and most widely used methods of oxidation using chromium (VI) involves the use of standard chromic acid/sulfuric acid solution which is simply titrated against a solution of the alcohol in acetone. This method is known as the Jones' oxidation reaction.³⁶ Acetone is an excellent solvent for a wide range of organic molecules. In this reaction it also protects the substrate from over-oxidation or undesired side reactions by reacting with the excess oxidant itself.³¹

1.2.1.2. Chromium (VI) with heterocyclic bases.

Chromium (VI) oxide is known to form complexes with several nitrogen heterocycles, many of which show oxidising powers. These are milder and thus more selective than the acid based reagent systems.³¹

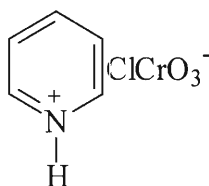
A chromium (VI) oxidation that is applicable to oxidations of acid sensitive substrates is the complex of chromium trioxide with two molecules of pyridine (10). This complex can

be synthesised by prolonged stirring of the solution formed from chromium oxide and pyridine. It was discovered by Collins and coworkers and it is known as the Collins reagent.³⁷ Standard oxidation conditions employ 6 equiv. of oxidant in dichloromethane and the reactions are normally complete within 5-15 min.³¹



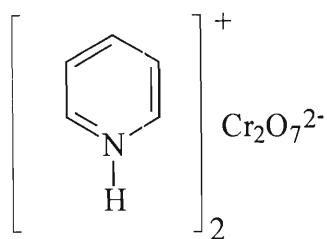
(10)

Pyridinium chlorochromate (PCC, 11) is a commercially available, stable yellow solid which is prepared by adding pyridine to a solution of chromium trioxide in hydrochloric acid.³⁸ It was first developed by Corey and coworkers³⁹ in 1977. With simple substrates, oxidations are normally performed in dichloromethane with 1.5 equiv. of oxidant, and are usually complete within 2 hours. The reaction time was successfully reduced by the addition of 3Å molecular sieves to the reaction mixture.⁴⁰



(11)

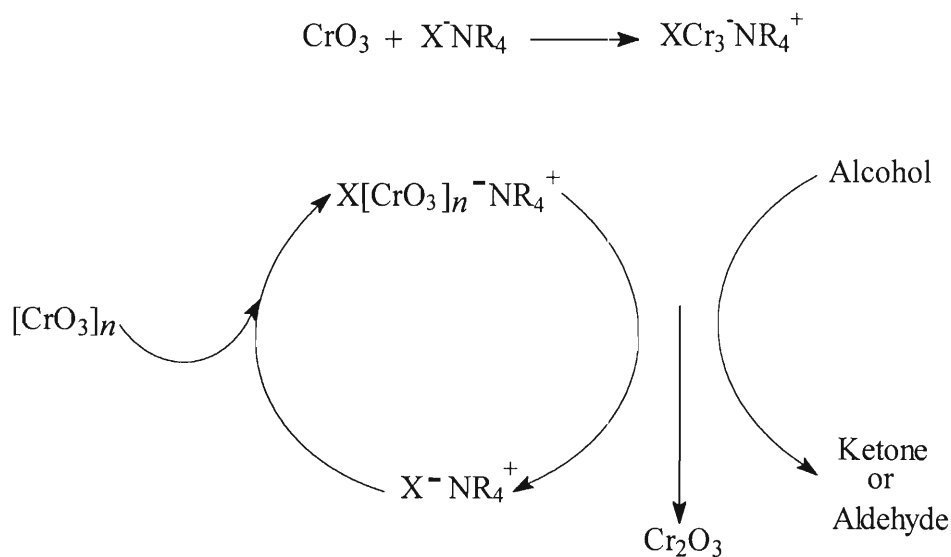
Pyridinium dichromate (PDC, 12) is an isolable, stable orange solid that can be simply and safely prepared by adding pyridine to a cooled solution of chromium trioxide in a minimum amount of water at a temperature lower than 30°C.^{38,41} Oxidations are carried out in dichloromethane using 1.5 equiv. of the oxidant in room temperature and are normally complete within 20 hours.³¹



(12)

1.2.1.3. Other chromium (VI) oxide reagents

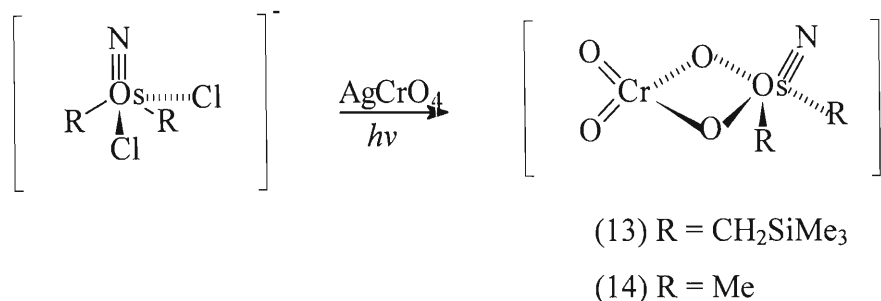
Gelbard and coworkers^{42,43} reported the use of tetraalkylammonium chromates for the oxidation of alcohols to aldehydes under mild, neutral conditions. They are more soluble than PCC in a number of organic solvents, and are readily prepared from chromium (VI) oxide and the appropriate tetraalkylammonium salt.⁴⁴ They may be used catalytically or stoichiometrically. However, catalytic oxidation is much more effective than the stoichiometric oxidation (Scheme 6).



Scheme 6

Shapley and coworkers have reported the preparation of two alkyl metal complexes; *cis*- $[\text{Bu}^n_4\text{N}][\text{Os}(\text{N})(\text{CH}_2\text{SiMe}_3)_2(\text{CrO}_4)]$ (13) and *cis*- $[\text{PPh}_4][\text{Os}(\text{N})\text{Me}_2(\text{CrO}_4)]$ (14) (equation 2),⁴⁴ that are thermally stable and inert to most standard organic solvents. Using air as the

cooxidant, these complexes oxidise primary alcohols to aldehydes and result in no overoxidation.

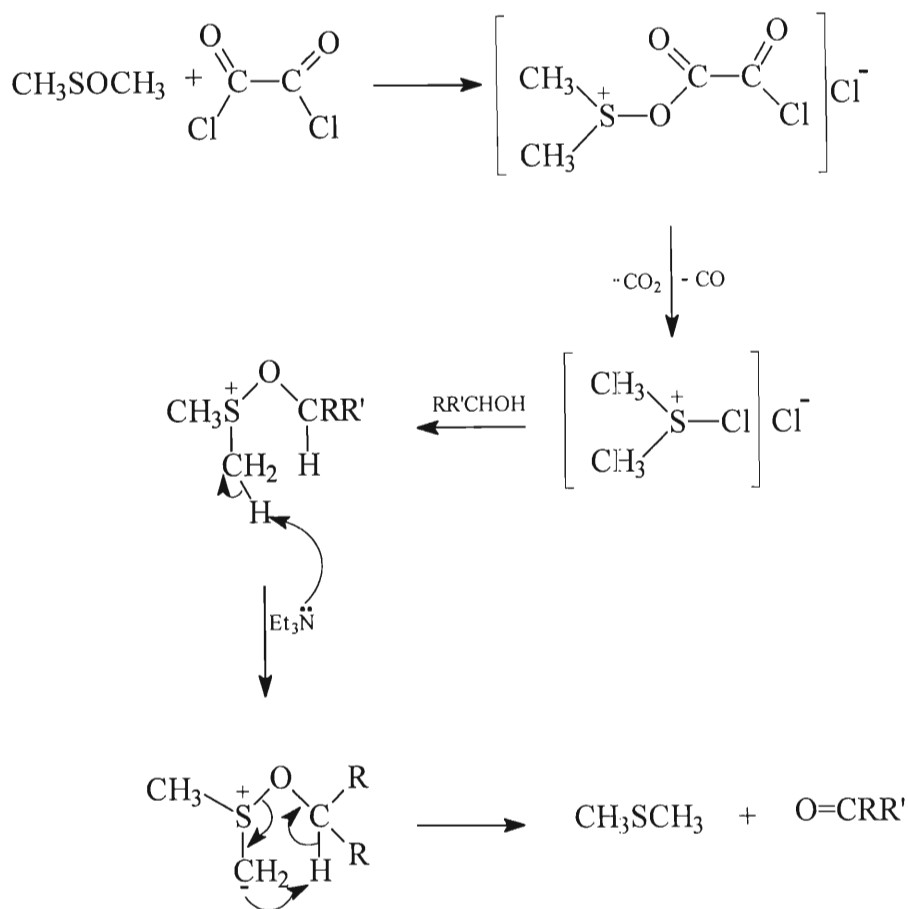


Equation 2

1.2.2. Dimethyl Sulfoxide Reagents

The nucleophilic nature of the sulfinyl oxygen of sulfoxides has been put to good use in synthetic chemistry, especially in the oxidation of alcohols to carbonyl compounds using dimethyl sulfoxide (DMSO).⁴⁵ Pfitzner and Moffatt⁴⁶ reported that DMSO can be used to oxidise primary alcohols to aldehydes without overoxidation to the carboxylic acid. In addition to DMSO, an activator is needed for the formation of a complex with the alcohol, and a base is required for the abstraction of a proton from the complex to initiate its collapse to the aldehyde. The course of the reaction is summarised in scheme 7.³⁸

The best activator seems to be oxalyl chloride (Swern oxidant)^{47,48,49}, but chlorine, phosgene, thionyl chloride, phosphoric acid, sulfur trioxide-pyridine, trifluoroacetic anhydride, acetic anhydride, dicyclohexylcarbodiimine, and other acyl chlorides and anhydrides give very good yields.³⁸



Scheme 7

1.2.3. Other Oxidants

A very simple and gentle oxidation of primary alcohols to aldehydes is their treatment in chloroform or carbon tetrachloride with a solution of dinitrogen tetroxide. The reaction is carried out at 0°C through room temperature and gives high yields of the desired aldehydes.³⁸

Very selective oxidising agents for the conversion of alcohols to aldehydes are high-potential quinones such as tetrachloro-*o*-benzoquinone, tetrachloro-*p*-benzoquinone, and 2,3-dichloro-5,6-dicyano-*p*-benzoquinone. These oxidants are used in chloroform, carbon tetrachloride, or ethanol, usually under very mild conditions, at room temperature or in refluxing ether.³⁸

A number of derivatives of ruthenium (II) have also been employed to oxidise primary alcohols to aldehydes. The ruthenium complex can be used as a catalyst in conjunction with a cooxidant such as *N*-methyldmorpholine *N*-oxide (NMO).^{50,51}

A catalytic method which promises to find wide application in view of its mildness and ease of execution uses a catalytic amount of tetra-*n*-propylammonium perruthenate (TPAP) or tetra-*n*-butylammonium perruthenate (TBAP) with NMO as the cooxidant.⁵² The performance of the reagent can be improved by the addition of molecular sieves to the reaction mixture.^{50,53}

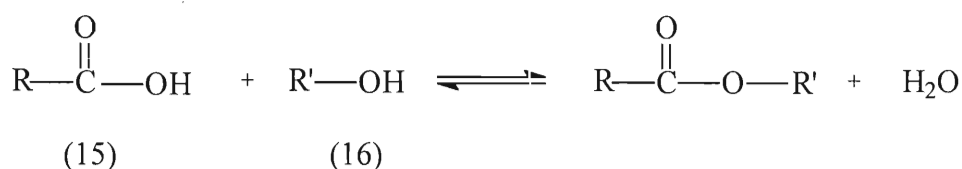
1.3. PREPARATION OF ESTERS FROM PRIMARY ALCOHOLS

The esters of carboxylic acids are an important group of compounds since they are used for a wide variety of chemical reactions and they are also frequently found as natural products. Esters may be formed directly from carboxylic acids or in other cases the alkoxy carbonyl group, -COOR, is derived from a less closely related functional group.⁵⁴ The following section deals with the most commonly used methods and/or reagents for the synthesis of esters.

1.3.1. Esterification

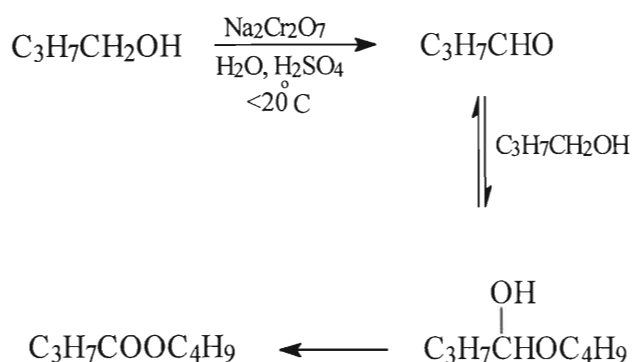
1.3.1.1. Carboxylic acids and alcohols

Esters are commonly formed by the reaction between a carboxylic acid (15) and an alcohol (16), the process being termed esterification (equation 3).⁵⁴ Acid-catalysed esterification is still frequently used for the synthesis of esters, particularly ethyl esters and methyl esters.⁵⁵ Sulfuric acid, hydrochloric acid,⁵⁶ and toluenesulphonic acid are the most commonly used acid catalysts and these can be used in the preparation of unsaturated esters, keto esters, halo esters, hydroxy esters, and alkoxy esters. Other catalysts, including boron trifluoride etherate⁵⁷ and a mixture of boric acid and sulfuric acid⁵⁸ can also be used for the esterification of a variety of alcohols.



Equation 3

During the oxidation of primary alcohols to aldehydes with acidic solutions such as chromic acid the aldehyde reacts with unchanged alcohol to form a hemiacetal which is rapidly oxidised to an ester (scheme 7).⁵⁹

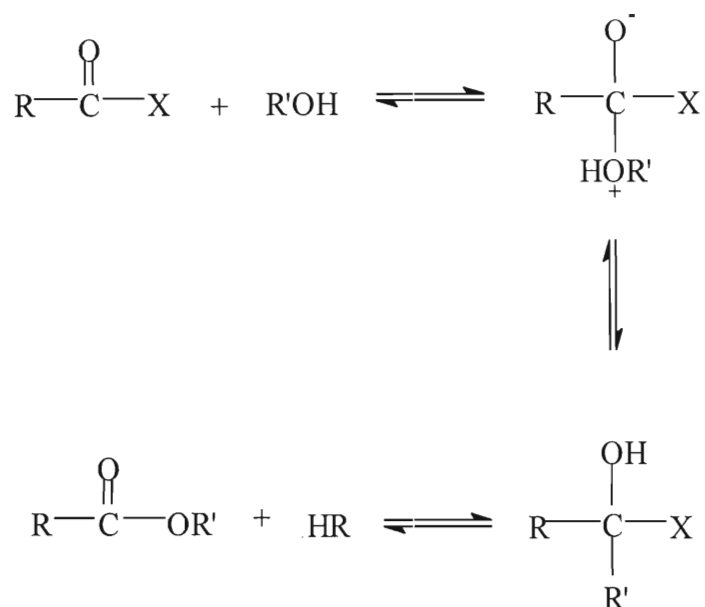


Scheme 7

1.3.1.2. Acylating agents and alcohols

Carboxylic acids are relatively poor acylating agents. However, in the reaction of a carboxylic acid derivative, RCOX, with an alcohol or an alkoxide anion, acylating ability increases in the series $X = \text{OH} < \text{NR}_2 < \text{OR} < \text{OCOR} < \text{Hal}$, where in general the stability of the anion X^- increases with increasing acylating ability (equation 4).⁵⁴

The most widely used acylating agents for ester synthesis are undoubtedly carboxylic acid halides ($X = \text{hal}$) and anhydrides ($X = \text{OCOR}$). There are many other compounds of the type RCOX which are effective agents for the synthesis of esters. A number of N-acyl heterocycles can also be used as acylating agent *e.g.* N-acylimidazoles.^{54,60}



Equation 4

1.3.1.3. Alkylation of carboxylate anions

Nucleophilic displacement by a carboxylate anion (RCO_2^-), normally under conditions where the $\text{S}_{\text{N}}2$ mechanism is followed, has been widely used for the synthesis of esters (equation 5). The reaction of diazomethane with carboxylic acids is a useful mild method for the preparation of methyl esters. 1-Alkyl-3-aryltriazenes also react with carboxylic acids to give esters.⁵⁴

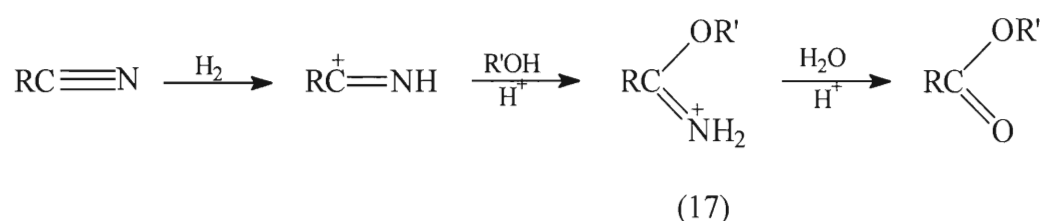


equation 5

1.3.2. Alcoholysis reactions

1.3.2.1. Nitriles and alkoxyimines

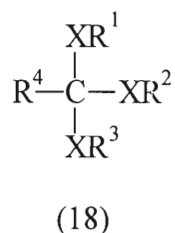
The acid-catalysed alcoholysis of nitriles (equation 6) is a well known alternative to the direct hydrolysis of nitriles to carboxylic acids. The acid catalyst is usually sulfuric acid, toluene-*p*-sulphonic acid, or hydrochloric acid and the water required for the final stage of the reaction may be present throughout the reaction or may be added after the initial formation of the alkoxyiminium salt (17).^{54,55} This reaction is generally used for the preparation of ethyl esters.



Equation 6

1.3.2.2. Ortho esters

Esters are formed by the controlled hydrolysis of ortho esters (18, X = O) or the corresponding sulphur analogues (18, X = S). This reaction has recently been used in a general synthesis of esters from aldehydes.⁶¹ This procedure avoids the use of the relatively vigorous oxidation reaction that are associated with such an interconversion.⁵⁴



1.4. SUPPORTED REAGENTS

1.4.1. Introduction

The early concept of a support or a carrier was that of an inert substance that provided a means of spreading out an expensive catalyst ingredient such as platinum for its most effective use, or a means of improving the mechanical strength of an inherently weak catalyst. However, a support may actually contribute catalytic activity, depending upon the reaction and reaction conditions, and it may react to some extent with other catalyst ingredients during the manufacturing process.⁶² Therefore, introduction of a certain agent onto or into an organic polymer or an inorganic support not only exerts a modified reactivity of the agent and/or specific product selectivity, but appreciably simplifies product isolation. Thus, supported reagents are currently offering attractive alternatives for organic syntheses.⁶³

Having a reagent or substrate attached to an insoluble support has several practical advantages which include the following:⁶⁴

- Reaction work-up is simplified because the supported species are easily separated from the non-supported species by filtration. This may make it possible to avoid exposing the reaction product(s) to water or avoid a chromatographic separation in the work-up.
- If the use of an excess of a reagent results in a greater reaction yield, then an excess can be used without causing separation problems.
- When a polymer-supported reagent is used, the spent reagent is easily recovered and can possibly be recycled. This is very important economically and can make it worthwhile to prepare complex supported reagents.
- If the reaction proceeds virtually to completion, so that filtration and washing of the polymer are all that is required to work-up the reaction, it becomes feasible to automate the process. This has obvious industrial benefits.

- If a reaction proceeds very readily it can possibly be carried out using a column of the supported reagent or substrate and passing the other reagent down the column.
- Since crosslinked polymers are insoluble and non-volatile, they are non-toxic and odourless. Hence carrying out reactions involving, for example, thiols and selenium compounds on polymer supports is a way of making the reaction environmentally more acceptable.

However, there are some difficulties associated with the preparation of these supported oxidant. The following are the common problems:⁶³

- Generally laborious preparation of a supported reagent.
- Necessity of meticulous care during the preparation of a supported reagent.
- Its relatively rapid deactivation on storage.
- A lack of generality ascribed to a trace amount of contaminant.
- Reduced utility due to lengthy preparations.

Hence, there is still a heavy demand for development of a manipulatively secure and simple technique to prepare a supported reagent.

The selection of a support is based on its having certain desirable characteristics. Principally they are:⁶²

- Inertness.
- Desirable mechanical properties *e.g.* hardness.
- Stability under reaction and regeneration conditions.
- Usually high surface area.
- Porosity.
- Low cost.

1.4.2. Types of Support Used

1.4.2.1. Alumina

A large variety of aluminas exist, in most cases distinguishable from one another by X-ray diffraction. Aluminas are generally prepared by dehydration of various aluminium hydroxides, but even if the hydroxide is a gel, it is readily converted to a crystalline form on aging and/or heating. The particular crystalline form obtained depends in a rather complicated way upon the time-temperature-environmental history to which the hydroxide is subjected, and this may be difficult to control, especially on a large scale. The aluminas contain water of constitution, which is slowly removed by heating.⁶²

The most important aluminas for use as supports are α -Al₂O₃ or η -Al₂O₃, which have high surface area and are relatively stable over the temperature range of interest for most catalytic reactions. The η form is inherently more acidic than the α form, which makes it more active for many acid-catalysed reactions.⁶²

1.4.2.2. Silica

Silica gel is most commonly prepared by mixing an acid with a solution of “water glass”, which consists of orthosilicates, metasilicates, and related compounds. As the pH is lowered, a polymerization and condensation process takes place, which can be visualised as starting with silicic acid. This polymerizes with condensation of silicane groups (SiOH) to form an ill-defined polymer in which the primary bonds are of the siloxane type (Si-O-Si).⁶²

The final dry product should strictly be referred to as a xerogel or porous silica, but silica gel is in common usage. At ambient temperature the surface consists of a layer of silanol groups plus physically adsorbed water. Most of the water is removed upon drying in air at 150 to 200°C.⁶²

Silica gel is generally more difficult to form than alumina. It is not as mechanically rugged, but is generally more inert.

1.4.2.3. Other supports

Kieselguhr is part of the natural siliceous deposits composed wholly of the shells of diatoms which are microscopic unicellular marine or fresh-water algae, remarkable for the silicified cell wall persisting as a skeleton after the death of the organism. These substances occur in friable masses, are light, loose, and powdery, of a fine and more or less uniform grain, and usually white or grey in colour.⁶⁵

Clay is a widely distributed earth, plastic and tenacious when moist but hard when baked. It consists of pure kaolin or, more commonly, of a mixture of kaolin with more or less finely eroded material, chiefly quartz, feldspar and mica, and is the result of the decomposition of granite and similar rocks. Kaolin is the purest form, and is used not only for the manufacture of porcelain, but also as a source of aluminium metal. It is a hydrous silicate of aluminium, $H_4Al_2Si_2O_9$, and is derived from the decomposition of aluminous minerals, especially feldspar.⁶⁶

All the above mentioned supports are inorganic supports. Poly (vinylpyridine) resin is an example of an organic support that was used in this research. The support is prepared from a solution of poly (vinyl alcohol) in boiling water. The addition of a solution of 4-vinylpyridine and divinylbenzene in toluene resulted in the resin after stirring overnight.⁶⁷ This resin can also be found commercially.

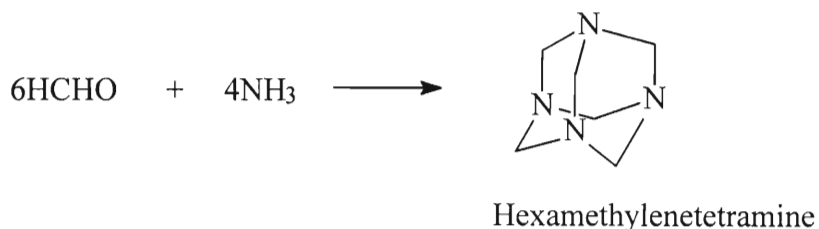
Other inert supports which can be used are graphite, charcoal, clay and polymeric matrix. However, these were not used in this research and thus they are not explained in details.

1.5 APPLICATION AND USES OF ALDEHYDES, ESTERS AND THEIR PRODUCTS.

Sasol produces a large quantity of alcohols from the F. T. syntheses. These alcohols can be used as organic solvents which have a good market both locally and internationally. They can also be used as plasticisers and detergents. However, surplus alcohols are still needed to be converted to useful forms such as aldehydes and esters.

The reactive unit consisting of a carbon double-bonded (C=O) to oxygen is known as the carbonyl group, and this functional group is responsible for the characteristic reactivity of aldehydes and esters. The carbonyl group is present in many substances of biological and commercial importance, and carbonyl compounds provide the essential ingredients for a large number of organic syntheses.⁶⁸

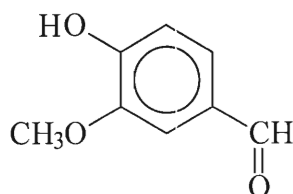
Formaldehyde, the simplest of the aldehydes, is considerably more reactive than its higher homologs. It is produced commercially by catalytic air oxidation of methanol and by the oxidation of hydrocarbon mixtures.⁶⁸ Its uses include preservation of biological specimens and embalming. The reaction of formaldehyde with ammonia result in a compound called hexamethylenetetramine which is used as a urinary antiseptic. It is also widely used as the starting material for the preparation of an explosive known as Cyclonite.⁶⁸



Acetaldehyde is produced commercially by the silver-catalysed air oxidation of ethanol and by the acid-catalysed hydration of acetylene. The main use of acetaldehyde is as an intermediate in the synthesis of other materials, including acetic acid, acetic anhydride, ethyl acetate, *n*-butanol, acrylonitrile, and acrylic esters. Acetaldehyde undergoes mixed

aldol condensation with formaldehyde to yield pentaerythriol which is used in the production of types of plastics known as alkyd and polyester resins.⁶⁸

Many aldehydes *e.g.* cinnamaldehyde and benzaldehyde have distinct odours which are used in industry. Vanillin has a characteristic vanilla odour and taste and is used as a flavouring compound in the food and beverage industry. It is produced commercially from the air oxidation of the alkaline mixture from the waste sulfite liquors of the pulp industry which then oxidise coniferyl alcohol to vanillin.⁶⁸

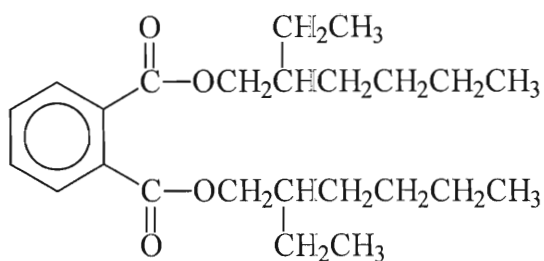


Vanillin

Furfural is a heterocyclic aldehyde which is used as an industrial solvent, a component in phenol-formaldehyde-type plastic, and as an intermediate in the synthesis of other useful organic compounds, including tetrahydrofuran.⁶⁸

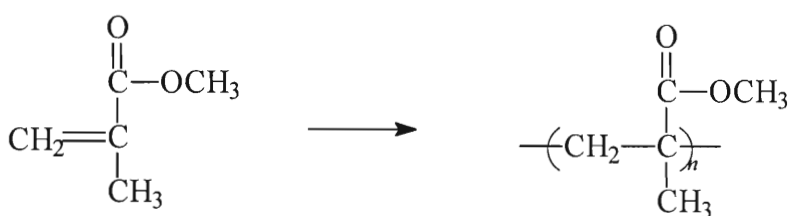
Most volatile esters have pleasant fruity odours, and many are used as synthetic flavouring agents and in perfumes. For example, the odours of isopentyl acetate, butyl butanoate, isopentyl valerate, methyl salicylate, and methyl anthranilate resemble the aromas of banana, pineapple, apple, wintergreen, and grapejuice respectively.⁶⁹

Di-2-ethylhexyl phthalate and other esters of phthalic acid are used as plasticisers, particularly in polyvinyl chloride.



Di-2-ethylhexyl phthalate

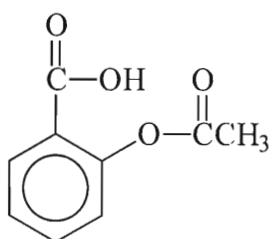
The polymer of the ester methyl methacrylate is used to manufacture windows, exterior construction panels, outdoor signs, and automobile tail lights. These esters are used because they are weather resistant.



Methyl methacrylate

Polymethyl methacrylate

An example of a biologically active ester is aspirin. It is prepared from the reaction of salicylic acid and acetic anhydride, and has analgesic (pain-reducing), antipyretic (fever-reducing), and anti-inflammatory actions.⁷⁰



Asprin

The aim of this research project was thus:

- To oxidise primary alcohols (C₃ - C₆) to their corresponding aldehydes.

- To oxidise primary alcohols (C₂ - C₆) to their corresponding symmetrical esters.
- To investigate the activity of different chromium (VI) compounds on different inorganic supports.
- To optimise the conditions of these supported oxidants.
- To try and reactivate the spent oxidants.

2. DISCUSSION

2.1. INTRODUCTION

The initial aim of this research project was to investigate the oxidation of ethanol, 1-propanol and 1-butanol to their respective aldehydes. However, due to the volatile nature of ethanal and propanal the alcohols which were oxidised were higher molecular weight alcohols *i.e.* C₄-C₆. Another problem with the lower molecular weight alcohols was the proximity of the boiling point of the respective aldehydes to those of solvents used in the experiments thus rendering the isolation of the aldehydes difficult.

A number of reagents are known to oxidise primary alcohols to aldehydes. The classical oxidants for the conversion of primary alcohols to aldehydes are compounds of hexavalent chromium. However, chromium in all its oxidation states is carcinogenic and a hazard to the environment. Therefore a system is required that will adsorb the chromium and still allow it to be active towards oxidation. Introduction of an insoluble inorganic support to these chromium compounds has previously been investigated.^{71,72}

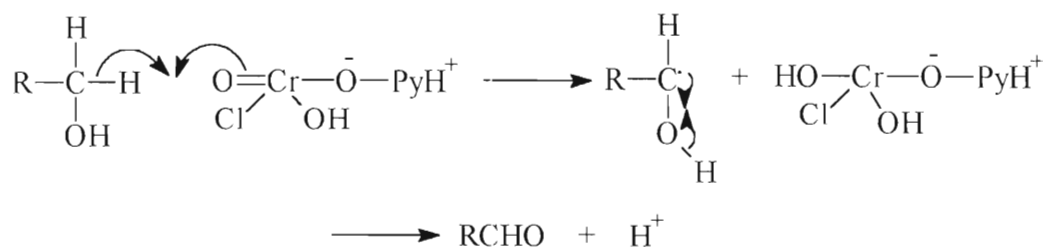
In this project, a number of supported oxidants were prepared and used to oxidise alcohols to aldehydes. These systems were chosen for a number of reasons most of which have been discussed in the previous section. During the study of the oxidation of alcohols to aldehydes some systems resulted in symmetrical esters. Fortunately esters are also of value to Sasol. As a result the oxidation of primary alcohols to symmetrical esters was also investigated. In addition to symmetrical esters, the preparation of unsymmetrical esters from different alcohols and aldehydes was also carried out.

2.2.1. Oxidation of alcohols to aldehydes with pyridinium chlorochromate (PCC).

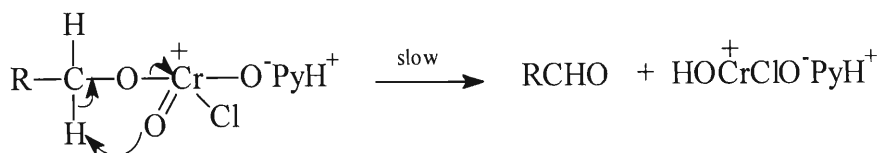
The main purpose of this experiment was the comparison of the reactivity of supported PCC and non-supported PCC. The chlorochromate anion was first used in 1933 by Peligot during the preparation of potassium chlorochromate.⁷³ PCC was first synthesised in 1899⁷⁴ and its reactivity was studied by Corey and coworkers.³⁹ They found that it oxidises a wide variety of alcohols to carbonyl compounds without over-oxidation to carboxylic acids.

PCC can be prepared by adding pyridine to a solution of chromium trioxide in 6 N hydrochloric acid followed by filtration to obtain the orange solid.³⁹ Corey and coworker used PCC to oxidise a wide range of alcohols to aldehydes.³⁹ Of particular importance to this project was the oxidation of 1-heptanol and 1-decanol to heptanal and decanal in dry dichloromethane. The yields obtained in their experiments were 78% and 92% for heptanal and decanal respectively.

The kinetics of the reaction were studied by Banerji.^{75,76} From the experimental data it was concluded that the rate determining step involves a C-H bond rupture. The hydride-ion transfer in the rate determining step may take place directly (Scheme 1) or may involve the prior formation of a chromate ester (Scheme 2).



Scheme 1



Scheme 2

The same reaction conditions were then used to oxidise 1-hexanol, 1-pentanol and 1-butanol and the reactions were complete in 1.5 hours. The progress of the reaction was monitored by GC-MS. When undistilled dichloromethane was used impurities resulted and no aldehyde was formed. The reaction was found to be moisture sensitive. The reaction was repeated in dry dichloromethane and a drying tube was used. The aldehydes were obtained in moderate yields (Table 1). The products formed were identified by GC-MS and NMR.

Table 1 Isolated yields of aldehydes from the oxidation with PCC.

ALDEHYDE	YIELD (%)
Hexanal	53
Pentanal	50
Butanal	50

The same reaction was carried out and 3Å molecular sieves were added to the reaction mixture. These played a dual role: they protected the reaction mixture from moisture as well as increase the reaction rate by favouring the cleavage of the C-H bond on the alcoholic carbon. This reaction was first used by Antonakis and coworkers^{77,78} during the oxidation of carbohydrates and nucleosides. The use of molecular sieves resulted in the reduction of the duration of the reaction to 30 min. The reaction afforded aldehydes in good yields (Table 2). According to Antonakis and coworkers 3 and 4Å molecular sieves were found to be more effective than bigger size molecular sieves. Only 0.5 g of the molecular sieves per mmol of the alcohol was required for effective oxidation of the alcohols.

Table 2 Isolated yields of aldehydes from the oxidation of the corresponding alcohols with PCC in the presence of molecular sieves.

ALDEHYDE	YIELD (%)
Hexanal	78
Pentanal	70
Butanal	75

Although molecular sieves were not used as a support in this reaction they eliminated the problem of difficult work-up by precipitating the chromium formed. In this way work-up only involved washing the residue with ether and evaporating the solvent. The use of molecular sieves in conjunction with PCC in dichloromethane was found to be effective in the oxidation of lower molecular weight alcohols to alcohols.

2.2.2. Oxidation of alcohols to aldehydes with silica gel-supported pyridinium chromate.

Chromic acid may be used in oxidation reactions as a complex of chromic acid and pyridine.^{79,80} However, since the preparation of chromic acid-pyridine complex is potentially hazardous, new useful reagents have been introduced.^{81,82} Another problem associated with the chromic acid-pyridine complex is the difficulty in working up the reaction mixture. A reagent which eliminates the problem of difficult work-up procedures was reported by Singh and coworkers.⁸³ In their study, they found that pyridinium chromate supported on silica gel oxidised alcohols to aldehydes and the work-up only involved filtration of the solvent.

Pyridinium chromate supported on silica gel can be prepared by adding silica gel to a solution of chromium trioxide in water then evaporating to dryness.⁸³ Pyridine is then added to the solid in light petroleum ether under anhydrous conditions, followed by drying. Pyridinium chromate is a brown free flowing powder which can be stored in a brown bottle at room temperature without losing its activity.

According to Singh and coworkers, the reagent has the capacity of 1.4 mmol of chromium trioxide per gram of the dried solid. The reagent was found to have a capacity of 1.5 mmol of chromium trioxide per gram of the reagent. The capacity was determined by reacting the reagent with Fe^{2+} and titrating the excess Fe^{2+} with dichromate.

The preparation of silica gel-supported pyridinium chromate differed to the one proposed by Singh and coworkers. They suggested that the mixture of silica gel and chromic acid be stirred for an hour. This was found to be impossible since the silica gel added was in excess. Therefore stirring or shaking the almost dry mixture was ineffective. A reagent prepared from shaking the mixture and the one prepared without shaking the mixture had similar results in the oxidation of alcohols. Again, during the addition of pyridine, it was almost impossible to stir the mixture with a magnetic stirrer thus posing a problem with keeping the reaction under anhydrous conditions because the reaction had to be stirred

manually. However, omission of these prolonged stirring did not seem to have an effect on the final product and the results obtained thereafter.

Singh and coworkers used the reagent (29 g) to oxidise a variety of alcohols (19 mmol) including 1-decanol in dichloromethane at room temperature (25-35°). These authors found that reaction of 1-decanol was complete within 4 hours and a 67% yield.

1-Hexanol (19 mmol) was oxidised following the method proposed by Singh and coworkers. The progress of the reaction was monitored by GC-MS. After 4 hours only 20% of the alcohol was converted to the aldehyde. The reaction was allowed to continue for over 48 hours with only 55% conversion. The quantity of hexanol was reduced to 14 mmol and the reaction stirred for 24 hours but still only 60% conversion was achieved. The initial quantity was then reduced to 10 mmol and the reaction was complete within 12 hours. 1-Pentanol and 1-butanol were then oxidised to their respective aldehydes in good yields using the reduced quantities (Table 3).

Table 3 Isolated yields of aldehydes from the oxidation of the corresponding alcohol with silica gel supported pyridinium chromate.

ALDEHYDE	YIELD (%)
Hexanal	62
Pentanal	65
Butanal	60

In an attempt to increase the rate of the reaction the temperature of the reaction mixture was increased to 35°C. This resulted in 20% yield of the aldehyde. The best yields were obtained when the reaction was carried out at 25-27°C. This was also confirmed by different results obtained when the reaction was carried out at night as opposed to during the day. It can therefore be concluded that the reaction is temperature dependent.

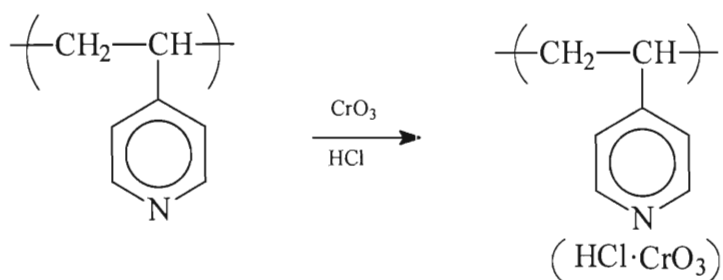
Of all the oxidations carried out using supported oxidants this reaction was the only reaction which required work-up after filtration of the solid reagent. The preparation of

this reagent is time consuming and the time required for the reaction to reach completion is long compared to other reactions.

The yields obtained in this experiment are similar to the ones obtained by Singh and coworkers. However, half of the quantity of the alcohol used by Singh and coworkers was used for the reaction to reach completion. The duration observed in this experiment was 12 hours while that observed by Singh and coworkers was 2 hours.

2.2.3. Oxidation of primary alcohols with poly[vinyl(pyridinium chlorochromate)]

The poly[vinyl(pyridinium chlorochromate)] reagent (PVPCC) can be prepared by the addition of stoichiometric amount of chromium trioxide and concentrated hydrochloric acid to a suspension of cross-linked poly(vinylpyridine) (PVP) in water (scheme 3).^{67,84} According to Fréchet and coworkers,^{67,84} the PVPCC resin has a capacity of 3.5-3.9 mmol of chlorochromate per gram. The reagent was found to have a capacity of 2 mmol of chlorochromate per gram of the reagent. The reagent can be used immediately after preparation without drying. This is an advantage since most supported reagents require lengthy drying time. The reagent can be dried for storage. As a result the shelf life of the reagent was indefinite.



Scheme 3

The reagent was used to oxidise 17 mmol of 1-hexanol and 1-pentanol in cyclohexane at 75°C. The choice of the alcohols was limited by the solvent and the temperature of the reaction. This is due to the fact that the aldehydes from lower molecular weight alcohols (C₂-C₄) have boiling points below that of the solvent. These aldehydes are therefore either lost due to evaporation or are difficult to separate from the solvent.

Table 4 Duration and yields from the oxidation of alcohols by PVPCC.

ALDEHYDE	TIME (DAYS)	YIELD (%)
Hexanal	3	70
Pentanal	2	75

Fréchet and coworkers found that the choice of solvent was very important. They concluded that nonpolar solvents such as heptane and cyclohexane produced the best

results. In general, it was found that the rate of reaction increased with decreasing solvent polarity. The rate of the reaction seem also to be dependent on the chain length of the alcohol. From table 4 the reaction of 1-hexanol was complete within 3 days while that of 1-pentanol was complete in 2 days. According to Fréchet and coworkers the reaction of 1-butanol was complete in 24 hours.

The temperature of the reaction is also important in increasing the rate of the reaction. The reaction at 75°C was found to result in 100% conversion while that at room temperature never reach completion. No products of over-oxidation were present in the reaction mixture.

According to Fréchet and coworkers, the spent PVPCC resin can be regenerated by washing with hydrochloric acid and sodium hydroxide. However, due to lengthy time of the reaction and high temperatures the resin was found to be damaged after the reaction. It was therefore impossible to validate the statement by Fréchet and coworkers that the reagent can be used more than once.

It has already been stated that the PVPCC reagent has a capacity of 2 mmol of chlorochromate per gram of the reagent. 10 grams of PVPCC was required to oxidise 17 mmol of the alcohol. This implies that an average of 1.1 mmol of chlorochromate was used to oxidise 1 mmol of the alcohol.

The results obtained in this experiment agree with those observed by Fréchet and coworkers. However, the reaction took longer than was observed by Fréchet and coworkers. The preparation of the supported oxidant does not require as much time. Besides the rather harsh conditions of the reaction this reaction can be considered best for the oxidation of primary alcohols to aldehydes.

2.2.4. Oxidation of alcohols to aldehydes and esters with silica gel-supported chromium trioxide.

The preparation of most of the supported oxidants reported thus far in the literature require adequate solvent removal and prolonged drying. In addition, these oxidations also require large excess of the oxidant and long reaction times. Khadilkar and coworkers⁸⁵ reported on a reagent which overcomes most of these problems.

Silica gel-supported chromium trioxide can be prepared by co-grinding pulverised chromium trioxide and silica gel, followed by activation at 100°C for 4 hours. The reagent is said to have a shelf life of at least 2 months when stored in a desiccator. According to Khadilkar and coworkers, the reagent has a capacity of 2 mmol of chromium trioxide per gram of the solid. However, the reagent was found to have a capacity of 1.8 mmol per gram of the reagent.

Khadilkar and coworkers used the reagent (20 mmol) to oxidise a variety of alcohols (20 mmol) including ethanol, 1-butanol and 1-octanol to their respective aldehydes in good yields. The reaction was carried out by stirring the reagent with the alcohol in dichloroethane at room temperature. The duration of the reactions ranges between 5 and 15 min. According to Khadildar and coworkers, the reagent oxidises primary alcohols to aldehydes without overoxidation to carboxylic acids.

The reagent was used to oxidise 1-hexanol, 1-pentanol and 1-butanol to their respective aldehydes in excellent yields (Table 5). The reaction was first carried out in dichloroethane following the method by Khadilkar and coworkers. The results of the reaction corresponded to those of Khadilkar and coworkers. However, the high boiling point of dichloroethane (79°C) imposed a limitation to the number of alcohols that could be oxidised using this method. Since dichloromethane is of a lower boiling point *i.e.* 40°C it was used as a solvent of choice. The use of dichloromethane resulted in yields similar to those obtained when dichloroethane was used. However, dichloromethane is a

chlorinated solvent thus it is hazardous to the environment. Ether was used in an attempt to replace dichloromethane but no reaction took place.

Table 5 Isolated yields and duration of the oxidation of alcohols with silica gel-supported chromium trioxide.

ALDEHYDE	TIME (MIN.)	YIELD (%)
Hexanal	12	80
Pentanal	12	80
Butanal	10	70

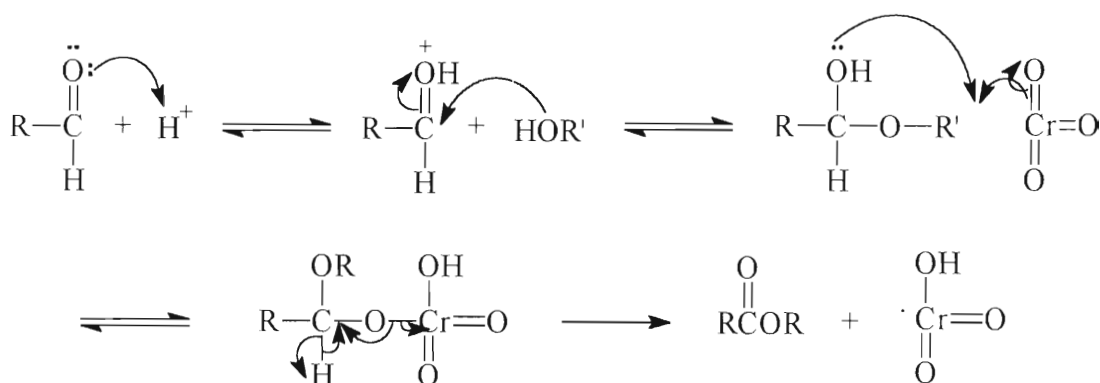
The reaction was first carried out during winter when room temperatures were approximately 12°C. In these conditions the oxidation was complete within 12 min. with aldehydes as products. When the same reaction was repeated in summer when room temperatures were approximately 24°C the reaction was complete in 30 min. and esters were the products (Table 6). It was therefore concluded that the reaction was temperature dependent.

Table 6 Isolated yields of esters obtained from the oxidation of alcohols with silica gel-supported chromium trioxide.

ESTER	YIELD (%)
Hexyl hexanoate	65
Pentyl pentanoate	75
Butyl butanoate	60
Propyl propanoate	65
Ethyl ethanoate	45

During the oxidation of alcohols, the presence of an alcohol and an aldehyde in solution establishes an equilibrium between these substances and a hemiacetal. The hemiacetal is formed by a nucleophilic addition of the alcohol to the carbonyl group (Scheme 4). Most open-chain hemiacetals are not sufficiently stable thus in this reaction they rapidly form

esters.⁸⁶ The fact that hemiacetal oxidation might be a road to esters was recognised by Schulz,⁸⁷ during the oxidation of decanol to decyl decanoate and a laural alcohol-decanal mixture (1:1) to obtain both decanoate and dodecanoate. The reaction was also examined by Craig and coworkers⁸⁸ during the oxidation of equimolar quantities of 1-hexanol and hexanal mixture. They observed that when ten-fold excess of the alcohol was used with one equivalent of both aldehyde and oxidant, the yield of the ester was 40%, and 56% of heptanal di-*n*-heptyl acetal was formed as well. These results suggest that the aldehyde, hemiacetal and acetal equilibrium was present. This was further confirmed by the absence of an ester when benzyl alcohol was oxidised under the same conditions. This is due to the failure of aromatic aldehydes to form hemiacetals.⁸⁹



Scheme 4

According to Khadilkar and coworkers⁸⁵ the stored reagent needs to be reactivated at 100°C for an hour before it can be used in a reaction. However, the reagent was used without activation and the results were not altered. The reagent was also activated for an hour to see if this has any effect on its activity. No difference was found in the yield and the duration of the reaction. Therefore, activating the reagent after storage was not necessary.

An attempt was made to regenerate the reagent after using it in an oxidation reaction. Initially hydrogen peroxide was used. No change in the colour of the reagent was seen. Potassium permanganate in an acidic medium was used to regenerate the reagent. This stripped the reagent of the chromium. The reagent was then heated at 350°C while blowing air over the solid and the process was carried out for 24 hours.⁹⁰ When this did not have an effect the temperature in the furnace was gradually increased to 800°C .

not have an effect the temperature in the furnace was gradually increased to 800°C. The colour of the reagent changed from dark brown to green. The green colour confirm the presence of Cr^{III}. The colour that was expected was light brown. However, the high temperature resulted in damage to the apparatus used to blow air. Our attempts to regenerate the reagent were then abandoned.

Besides the change in the solvent the results obtained in our laboratory are similar to the ones obtained by Khadilkar and coworkers. However, they reported that this oxidant result in no overoxidation while esters were obtained as a result of further esterification.

2.2.5. Oxidation of alcohols to aldehydes and esters with chromium trioxide.

During their work on complexes of oxodiperoxychromium (VI) with pyridine⁹¹ and ether⁹², Flatt and co-workers⁹³ observed that the addition of chromium trioxide to a solution of an alcohol in a mixture of diethyl ether and dichloromethane (1:3) in the presence of celite results in the oxidation of alcohols to carbonyl compounds. In this reaction celite does not act as a support but performs the role inert inorganic supports do. It presumably adsorb the lower valent chromium species produced during the oxidation.

Flatt and coworkers⁹³ oxidised a variety of alcohols including 1-pentanol and 1-nonanol to their respective aldehydes in 54% and 52% respectively. The reaction was carried out by adding chromium trioxide to a mixture of celite and the alcohol in dichloromethane and diethyl ether. The texture of chromium trioxide affects the rate of the reaction. Pulverised chromium trioxide is the best to use in this reaction. The ratio of dichloromethane to diethyl ether is also very important. It was found that the optimum ratio of dichloromethane to diethyl ether was 3:1.

When chromium trioxide was added to a solution of an alcohol in dichloromethane in the absence of ether and celite, no oxidation took place. This is due to the fact that chromium trioxide is insoluble in dichloromethane.⁹⁴

The oxidising species in this reaction is thought to be either a diethyl ether/chromium trioxide complex or a colloidal suspension of chromium trioxide.⁹³ This species is very unstable hence the sequence of addition of chromium trioxide to the reaction mixture is important. It is more efficient to add chromium trioxide to a solution of the alcohol and ether than to add alcohol to pre-formed diethyl ether/chromium trioxide reagent. The addition of alcohol to diethyl ether/chromium trioxide result in no oxidation taking place.

The chromium trioxide/diethyl ether reagent was used to oxidise 1-hexanol, 1-pentanol and 1-butanol to their respective aldehydes in moderate yields (Table 7). The results obtained correspond to those obtained by Flatt and coworkers.

Table 7 Isolated yields of aldehydes from the oxidation with chromium trioxide.

ALDEHYDE	YIELD (%)
Hexanal	52
Pentanal	49
Butanal	50

The reaction was initially carried out at room temperature. The rate of the reaction was found to be very slow. However, when the reaction was carried out in an ice bath the reaction resulting in aldehydes was complete within 20 min. The reaction was then left to run for longer than 20 min at room temperature. The product was found to be an ester. 1-Hexanol, 1-pentanol, 1-butanol, and 1-propanol were oxidised to their respective esters in good yields (Table 8). The yields of esters were better than those of aldehydes.

No product was found from the oxidation of ethanol to ethyl acetate. However, GC-MS analysis of the reaction mixture showed that ethyl ethanoate was present in small quantities. Flatt and coworkers reported that the reagent only result in carboxylic acids when an excess of chromium trioxide is used.

Table 8 Isolated yields of esters from the oxidation with diethyl ether/chromium trioxide system.

ESTER	YIELD (%)
Hexyl hexanoate	60
Pentyl pentanoate	60
Butyl butanoate	58
Propyl propanoate	50

This reaction does not employ celite as a support but only to adsorb the residual chromium.⁹³ Celite is very fine thus problems were experienced during the filtering of the mixture. Besides the problem of filtering, this reaction was found to be good in terms of rapid product formation and the fact that both aldehydes and esters can be produced by manipulating reaction conditions.

2.2.6. Oxidation of alcohols to esters with alumina-supported chromium trioxide.

Most of the known supported reagents require lengthy preparation times and they rapidly deactivated on storage. Morimoto and coworkers⁶³ reported a supported oxidant which is not affected by the above mentioned factors.

Alumina-supported chromium trioxide can be prepared by mixing “wet” alumina with pulverised chromium trioxide and then stirring the mixture in hexane. “Wet” alumina is a term given to moist alumina. Removal of the solvent by filtration result in a brown free-flowing powder which can be used immediately. No lengthy drying is required. The reagent can be kept in a dessicator for several weeks without losing its activity. According to Morimoto and coworkers the reagent has a capacity of 1.7 mmol of chromium trioxide per gram of the dried solid.

15 g of the reagent was used to oxidise 1 mmol of 1-hexanol, 1-pentanol, 1-butanol and 1-propanol in hexane at room temperature for 24 hours to their respective symmetrical esters in good yields (Table 9).

Table 9 Isolated yields obtained from the oxidation with alumina-supported chromium trioxide.

ESTER	YIELD (%)
Hexyl hexanoate	75
Pentyl pentanoate	72
Butyl butanoate	65
Propyl propanoate	70

According to Morimoto and coworkers the use of an inert atmosphere in anhydrous conditions during the reaction prohibits the overoxidation of aldehydes to carboxylic acids.⁶³ Since our initial product was an ester, attempts were made to inhibit over-oxidation through an inert atmosphere. Argon was bubbled through the reaction mixture and the progress of the reaction monitored by GC-MS. Instead of prohibiting

esterification the inclusion of argon only slowed the rate of reaction. The reaction was complete in 40 hours rather than 24 hours as in the absence of argon. Attempts were made to stop the reaction at the aldehyde stage but this was not successful. As soon as the aldehyde was formed it reacted with the remainder of the alcohol to form the ester.

Less oxidant was used in an attempt to obtain aldehydes rather than esters (Table 10). 5 g of the reagent resulted in very little oxidation. However, both aldehyde and ester were present from the GC-MS analysis. Although 10 g of the reagent resulted in better oxidation than 5 g, the reaction was still not complete. Again, both the aldehyde and the ester were present in the reaction mixture.

The quantity of the solvent was also varied to determine the effect of concentration. It was found that the use of 100 ml or 80 ml didn't have an effect on the results. However, the use of 50 ml of hexane resulted in little oxidation. Therefore, the amount of solvent used in the reaction was found to be important in the reaction rate.

Table 10 effect of concentration and oxidant quantity in the oxidation of 1-hexanol.

REAGENT (G)	HEXANE(ML)	HEXANOL(%)	HEXANAL(%)	HEXYL HEXANOATE (%)
15	100	0	0	100
15	80	2	2	96
15	50	80	15	5
10	100	60	10	30
5	100	90	5	5
5	50	80	5	15

Different solvents were used to determine if other solvents rather than hexane can be used in this reaction. Diethyl ether and chloroform were used. Addition of the alcohol to the mixture of diethyl ether and the reagent resulted in a brown mixture similar to the one observed with hexane. However, no ester or aldehyde was isolated. GC-MS analysis of

the reaction mixture showed that no ester was available either. Addition of the alcohol to the chloroform mixture did not have any effect. No colour change was observed and no ester was isolated either.

The reaction was also carried out at room temperatures and at 60°C to determine whether the reaction was temperature dependent. The reaction at 60°C resulted in unknown products and no ester was isolated. The reaction at room temperature resulted in esters in good yields.

In an attempt to explain the formation of esters equimolar quantities of the alcohol and the aldehyde were used in a reaction to determine whether the ester would form under these conditions. Whether the alcohol or the aldehyde was added first or the mixture of the two does not affect the results of the reaction. The yields obtained from this reaction were better than the ones obtained from the oxidation of the alcohol to the ester under the same reaction conditions (Table 11).

Unsymmetrical esters were also synthesised in good yields following the success of symmetrical esters (Table 11). These were synthesised from the oxidation of hexanal with different alcohols.

Table 11 Isolated yields obtained from the oxidation of the combination of aldehydes and alcohols to form esters with alumina supported chromium trioxide.

ESTER	YIELD (%)
Hexyl hexanoate	95
Pentyl pentanoate	92
Butyl butanoate	88
Propyl propanoate	80
Pentyl hexanoate	77
Butyl hexanoate	85
Propyl hexanoate	80

An attempt was made to regenerate the oxidant. Hydrogen peroxide was first used but no colour change was observed. The colour was expected to change from dark brown to light brown. Potassium permanganate was also used but resulted in stripping the chromium off the support. Finally, the reagent was heated in a furnace at 350°C and air was blown in for 24 hours.⁹⁰ The colour of the reagent changed from brown to green. The green colour confirms the presence of chromium (III). It was believed that increasing the temperature to 800°C would convert the reagent to the desired reagent. However, this was unsuccessful as well.

2.2.7. Oxidation of primary alcohols to esters with kieselguhr-supported chromic acid.

Chromic acid supported on inert inorganic supports such as graphite⁹⁵, silica gel⁹⁶, charcoal⁹⁷ and aluminium silicate⁹⁸, are oxidants for the oxidation of alcohols to aldehydes. Lou⁹⁹ recently reported the use of chromic acid supported on kieselguhr as one of the reagents suitable for the oxidation of primary alcohols to aldehydes.

The reagent can be prepared by adding kieselguhr to a solution of chromium trioxide in water then evaporating to dryness. The reagent can be used after drying at 100°C for 5 hours. The reagent was found to have a capacity of 1 mmol per gram of the dried solid. According to Lou the reagent can be kept in vacuum in the dark for at least six weeks without losing its activity. The validity of this statement was not investigated.

Lou used the reagent (18 g) in petroleum ether at room temperature (60-80°) to oxidise 20 mmol of 1-propanol, 1-butanol and 1-pentanol to their respective aldehydes in good yields. No mention is made of overoxidation to the carboxylic acid nor of the possibility of esterification.

Following the procedure by Lou the reagent was used to oxidise each of the following alcohols: ethanol, 1-propanol, 1-butanol, 1-pentanol and 1-hexanol. The results obtained differ from those observed by Lou. Oxidation of the above mentioned alcohols using the method by Lou resulted in symmetrical esters of the alcohols in good yields (Table 12). Since the boiling point of ethyl acetate is lower than that of petroleum ether (60-80°), its isolation was impossible. The GC-MS analysis of the ethanol reaction showed that all the alcohol was converted to the ester.

Table 12 Isolated yields obtained from the oxidation and subsequent esterification of alcohols with kieselguhr supported chromic acid.

ESTER	YIELD (%)
Hexyl hexanoate	85
Pentyl pentanoate	85
Butyl butanoate	60
Propyl propanoate	40

The progress of the reaction was monitored by GC-MS. It was discovered that the reaction formed the ester as soon as there was an excess of the alcohol. In this case, the alcohol reacts with the aldehyde to form the ester in conjunction with the oxidation of the alcohol to the aldehyde. It was therefore impossible to stop the reaction so that the aldehyde could be isolated.

Diethyl ether was used as a solvent in the oxidation of 1-hexanol instead of petroleum ether in an attempt to slow down the reaction. The reaction was initially exothermic as seen with the reaction in petroleum ether but the product was contaminated. Therefore diethyl ether cannot be used as a replacement for petroleum ether.

Finally, argon was employed in an attempt to stop esterification. The reaction was run under the same conditions except that an argon atmosphere was used as suggested by Morimoto and coworkers⁶³. The reaction was found to be slower, *i.e.* the reaction was not complete within an hour as was the case with the other reactions. The progress of the reaction was also followed by GC-MS in order to stop the reaction after the formation of the aldehyde. It was found that as soon as the aldehyde formed it reacted with the alcohol to form an ester. GC-MS therefore showed the presence of the alcohol, aldehyde and ester in varying quantities during the course of the reaction. It was therefore impossible to control the reaction to form only the aldehydes. The use of an inert atmosphere was not successful in stopping the formation of an ester.

Equimolar quantities of the aldehyde and the alcohol were reacted to determine if the ester would form. The conditions of the reaction were not altered. The esters were isolated in yields better than the yields obtained from the oxidation of alcohol (Table 13). Both symmetric and unsymmetric esters were synthesised.

Table 13 Isolated yields from the synthesis of esters from a combination of alcohols and aldehydes.

ESTER	YIELD (%)
Hexyl hexanoate	90
Pentyl pentanoate	89
Butyl butanoate	85
Propyl propanoate	79
Pentyl hexanoate	77
Butyl hexanoate	80
Propyl hexanoate	79

The results observed in this experiment differ tremendously to those of Lou. Instead of aldehydes, esters were obtained as products (see page 42 for the proposed mechanism of the formation of esters). Lou made no mention of the possibility of the formation of esters.

2.2.8. Oxidation of alcohols to esters with aluminium silicate-supported chromic acid.

Lou and Wu⁹⁸ recently reported on an aluminium silicate-supported chromic acid reagent that can be used to oxidise primary alcohols to aldehydes. This reagent can be prepared by addition of aluminium silicate to a solution of chromium trioxide in water followed by the removal of water *in vacuo*. This is then followed by drying the reagent at 100°C for 6 hours. The reagent was found to have a capacity of 1.1 mmol per gram of the dried solid. This long preparation time is one of the disadvantages of the preparation of supported oxidants. The yellow solid obtained can be kept under vacuum in the dark for several weeks without losing its activity.

Lou and Wu used the reagent to oxidise ethanol, 1-propanol, 1-butanol and 1-pentanol to their respective aldehydes in yields ranging from 74-85%. The reaction was carried out by stirring the reagent (37 g) in petroleum ether (60-80°) followed by adding the mixture of the alcohol (25 mmol) in petroleum ether.

The reagent was used following the method by Lou and Wu to oxidise ethanol, 1-propanol, 1-butanol, 1-pentanol and 1-hexanol. However, instead of aldehydes, esters were obtained in good yields (Table 14). Ethyl acetate was not isolated but the GC-MS analysis of the reaction mixture showed that all the alcohol was converted to ethyl acetate. No change was made in the duration nor the quantities used by Lou and Wu. No mention is made by Lou and Wu of the possibility of overoxidation or esterification. The duration of the reaction varied depending on the alcohol being oxidised. It was discovered that the time required for the oxidation was independent of the chain length of the alcohol.

Table 14 Isolated yields and duration of the oxidation of primary alcohols to esters with aluminium silicate-supported chromic acid.

ESTER	TIME (H)	YIELD (%)
Hexyl hexanoate	48	63
Pentyl pentanoate	48	69
Butyl butanoate	24	50
Propyl; propanoate	48	49

The reaction was found to be exothermic in its early stages but soon the temperature reached room temperature. This factor was exploited in an attempt to slow down the reaction so that aldehydes were the only products isolated. The reaction was carried out in an ice bath to lower the temperature. This did not change the results of the reaction. It was therefore concluded that the reaction was not temperature dependent.

The initial quantity of 36 g of the reagent was decreased in an attempt to oxidise the alcohol to the aldehyde (Table 15). The other variables remained unchanged. The use of 9 g of the reagent resulted in an incomplete reaction. The quantity was increased to 18.5 g and still the reaction was incomplete. Changing the amount of solvent used in the reaction resulted in a slight decrease in the rate of the reaction. Doubling the quantity of the solvent did not have much of an effect. However, when three times the original solvent was used the rate of the reaction was slowed down. The quantity of the solvent could not be halved due to ineffective stirring experienced when little solvent is used.

Table 15 Effect of changing the quantity of the solvent and the supported reagent.

REAGENT(G)	PETROLEUM ETHER(ML)	HEXANOL(%)	HEXANAL(%)	HEXYL HEXANOATE (%)
18.5	45	40	10	50
9	45	50	10	40
37	90	2	2	98
37	135	10	10	80

The oxidation and subsequent esterification of the combination of alcohols and aldehydes was also carried out to determine the yields obtained by this method. Symmetric and unsymmetric esters were synthesised in good yields. These yields were found to be better than those of the oxidation of alcohols to esters (Table 16). The duration of the reaction was also reduced.

Table 16 Isolated yields of esters from the oxidation and subsequent esterification of a combination of alcohols and aldehydes.

ESTER	TIME (H)	YIELD (%)
Hexyl hexanoate	36	85
Pentyl pentanoate	36	77
Butyl butanoate	20	82
Propyl propanoate	36	80
Pentyl hexanoate	36	80
Butyl hexanoate	36	75
Propyl hexanoate	36	60

The results obtained differ from those obtained by Lou and Wu in that instead of aldehydes esters were the products. However, the duration of the reaction and the concentration of reagents were the same as those reported by Lou and Wu.⁹⁸

2.2.9. Oxidation of alcohols to esters with alumina-supported pyridinium chlorochromate.

The use of pyridinium chlorochromate in the oxidation of primary alcohols to aldehydes is one of the best known oxidation methods in organic chemistry. However, this reaction is associated with problems of difficult work-up. Cheng and coworkers¹⁰⁰ recently reported the use of PCC supported on alumina as a reagent for the oxidation of primary alcohols to aldehydes without overoxidation to the carboxylic acid. The reagent was introduced to overcome problems of work-up experienced when using PCC.

The reagent is easily prepared by adding pyridine to a solution of chromium trioxide in 6N hydrochloric acid followed by the addition of alumina. Evaporation of excess water results in a yellow solid. The reagent can be stored in vacuum at room temperature in the dark for several weeks without losing its activity. The reagent is said to have the capacity of 1mmol of chlorochromate per gram of the dried reagent.¹⁰⁰ However, the reagent was found to have capacity of 1.8 mmol per gram of the dried solid.

Cheng and coworkers didn't specify which type of alumina was used in their experiments. As a result neutral, basic and acidic alumina were used to determine which of the three was the best. The results obtained were similar. Since primary alcohols were oxidised, it was expected to isolate carboxylic acids from the oxidation with acidic alumina. Since the type of alumina did not seem to affect the outcome of the reaction, it was decided to use neutral alumina for all the experiments.

Cheng and coworkers used 37.5 mmol of the reagent to oxidise 19 mmol of the alcohol in hexane at room temperature. The reaction was stirred for 2 hours. A wide variety of alcohols were oxidised to their respective aldehydes in yields ranging between 45 and 94%. The method was then used to oxidise 1-hexanol. The results obtained differed from those obtained by Cheng and coworkers. Instead of 19 mmol of the alcohol, 14.7 mmol was used to achieve 90% conversion of the alcohol to the ester rather than the aldehyde.

The reaction took longer than the 2 hours observed by Cheng and coworkers. After 2 hours both the aldehyde and the ester were present in the reaction mixture. The reaction was allowed to stir first for 12 hours and then for 24 hours to determine the optimum time required for maximum conversion. The results of the different durations were found to be similar and thus the subsequent reactions were stirred for 12 hours. 1-Pentanol, 1-butanol and 1-propanol were then oxidised following the method obtained in this experiment. The esters were obtained in moderate to fair yields (Table 17).

Table 17 Isolated yields obtained from the oxidation and subsequent esterification of alcohols with alumina-supported PCC.

ESTER	YIELD (%)
Hexyl hexanoate	51
Pentyl pentanoate	45
Butyl butyrate	32
Propyl propionate	35

The reaction was also carried out at different temperatures (Table 18). The results obtained when the reaction was carried out at 15°C were found to be the same as the results obtained at 25°C. The temperatures were varied by running the reaction at night and during the day. A number of problems were experienced when the reaction was carried out at 60°C. The high temperature resulted in hardening of the reagent thus resulting in difficulty in stirring. No ester was present from the GC-MS analysis. Therefore an increase in temperature was not beneficial for this reaction.

Table 18 Percentage conversion of 1-hexanol to hexyl hexanoate under different temperature conditions.

TEMPERATURE °C	CONVERSION %
12	90
25	90
60	0

Equimolar amounts of both the alcohol and the aldehyde were added in the reaction mixture to confirm the kinetics of the reaction. The formation of the expected ester was achieved in 4 hours. The yields obtained from this reaction are better than the ones from the oxidation of the alcohol. Symmetrical and unsymmetrical esters were synthesised from this reaction (Table 19).

Table 19 Isolated yields from the oxidation of the combination of alcohols and aldehydes to esters.

ESTER	YIELD (%)
Hexyl hexanoate	62
Pentyl pentanoate	65
Butyl butanoate	59
Propyl propanoate	60
Pentyl hexanoate	70
Butyl hexanoate	65
Propyl hexanoate	66

These results are different to the results obtained by Cheng and coworkers. Instead of the aldehydes, esters were obtained as products and the duration of the reaction was longer than the one observed by Cheng and coworkers. The reason for this might be due to the different alcohols used. They used mainly cyclic alcohols in their experiments. However, there should be no reason why the different alcohols should result in different products. Another reason might be the difference in the capacities of the reagents used. The reagent used by Cheng and coworkers had a capacity of 1 mmol per gram while the one used in this experiment was found to have a capacity of 1.8 mmol.

Due to the different products obtained this reaction cannot be compared with the reaction of PCC. However, the ease of performing this reaction compared to that of PCC cannot be ignored. The reaction is also better in terms of the solvent used. The reaction of PCC used dichloromethane as the solvent while hexane was used in this experiment. However,

the PCC reaction was found to be better in terms of the time it required to run the reaction. The reaction of PCC with molecular sieves was complete within 30 min. while this reaction requires 12 hours to reach completion.

2.3. CONCLUSION AND FUTURE PROPOSALS

The initial aim of this research project was to oxidise C₂-C₄ alcohols to their respective aldehydes. However, numerous problems were encountered during the oxidation and the alcohols had to be changed to C₄-C₆ alcohols. The purpose of using these alcohols was to determine if the oxidation systems work so that they can be applied to the desired alcohols. However, application of some of these systems to the desired alcohols will require specialised equipment in order to successfully separate the respective aldehydes from the solvent system. Care should also be taken to avoid the evaporation of the volatile aldehydes.

Different supported oxidants were used to oxidise primary alcohols to aldehydes. Some of the systems resulted in esters instead of aldehydes. The oxidation of primary alcohols to esters was then also investigated. Since esters have higher boiling temperature compared to aldehydes C₂-C₆ alcohols were used in the oxidation to esters. The only way for one to determine the best system is by comparison of all the systems used.

Comparison of the oxidation systems used.

Oxidation of alcohols with PCC

As has already been mentioned, the purpose of this experiment was to serve as a basis of comparison between supported and non-supported PCC. PCC can be prepared easily and safely or it could be bought if time is of essence. In this experiment 75 mmol of PCC was used to oxidise 50 mmol of the alcohol. The reaction was complete within 30 min and it resulted in good yields of the aldehyde. The solvent used for this experiment was dichloromethane which is not favourable environmentally since it is chlorinated. Since no supported oxidant was used no lengthy drying was required except during the preparation of PCC.

Oxidation of primary alcohols with silica gel-supported pyridinium chromate.

The preparation of the reagent was lengthy and also required long drying time. During the preparation care had to be taken to make sure that the temperature of the mixture is constant. The reagent has a capacity of 1.5 mmol of chromium trioxide per gram of the dried solid. The reagent can be stored for over a year at room temperature in the dark without losing its activity. 29g of the reagent was used to oxidise 15 mmol of the alcohol in dichloromethane at room temperature for 12 hours. From the capacity of the reagent it can be calculated that 43.5 mmol of chromium trioxide is required to oxidise 15 mmol of the alcohol. This implies that an average of 2.9 mmol is required to oxidise 1 mmol of the alcohol. The reaction resulted in good yields of the aldehydes.

Oxidation of primary alcohols with PVPCC.

The preparation of the reagent requires only an hour and no drying of the reagent is necessary if the reagent is to be used immediately. Drying is only required if the reagent is to be stored. The reagent has a capacity of 2 mmol of chlorochromate per gram of dry polymer. 20 g of the reagent is required to oxidise 34 mmol of the alcohol in cyclohexane at 80°C for over 24 hours. It is said that only 1.7 mmol of chlorochromate is used the reaction. This implies that 34 mmol of chlorochromate oxidises 34 mmol of the alcohol, *i.e.* 1 mmol of chlorochromate oxidises 1 mmol of the alcohol. The reaction resulted in good yields of the aldehydes.

Oxidation using silica gel-supported chromium trioxide.

The preparation of the reagent is easy and only require a short time for activating. The reagent is said to have a shelf life of about 2 months when stored in a dessicator. It also has a capacity of 2 mmol of chromium trioxide per gram of the solid. 10 g of the reagent is required to oxidise 20mmol of the alcohol and the reaction is complete within 12 min. Therefore, 20 mmol of chromium trioxide is required to oxidise 20 mmol of the alcohol. This implies that 1 mmol of chromium trioxide oxidises 1 mmol of the alcohol. The

reagent resulted in excellent yields of both the alcohols and the esters. The solvent used for this experiment was dichloromethane. This is by far the best methods used in this research. It result in excellent yields. The preparation of the reagent and duration of the reaction are not time consuming.

Oxidation with diethyl ether/chromium trioxide.

This is another reaction which was used as a basis for comparison for supported and non-supported chromium trioxide. No preparation of the reagent is required since chromium trioxide is used as is. 75 mmol of chromium trioxide is required to oxidise 50 mmol of alcohol in dichloromethane and diethyl ether. The reactions are complete within 15 min. for aldehydes and 20 min. for esters. The reaction resulted in moderate yields of the aldehydes and good yields of the esters. This is another good reaction since it result in both the aldehydes and esters depending on the duration of the reaction.

Oxidation with alumina-supported chromium trioxide.

This is one of the best reagents in terms of the preparation. The preparation is easy and no lengthy drying is required. The reagent has a shelf life of up to 6 weeks when stored in a dessicator. The reagent was found to have a capacity of 2.1 mmol of chromium trioxide per gram of the solid. 15 g of the reagent was used to oxidise 10 mmol of the alcohol at room temperature and the reaction was complete in 24 hours. Therefore 31.5 mmol of chromium trioxide was used to oxidise 10 mmol of the alcohol. On average 3.1 mmol of chromium trioxide is required to oxidise 1mmol of the alcohol. The solvent used for this experiment was hexane which is favourable environmentally. The reaction resulted in good yields of the esters.

Oxidation with kieselguhr-supported chromic acid.

The preparation of the reagent require lengthy drying times. The reagent has a shelf life of up to 6 weeks when stored in a dessicator. 18 g of the reagent is required to oxidise 20

mmol of the alcohol in petroleum ether and the reactions are complete within an hour. The capacity of the reagent was found to be 1 mmol of chromium trioxide per gram of the dried solid. This implies that an average of 0.9 mmol of chromium trioxide was required to oxidise 1 mmol of the alcohol. The reaction resulted in good yields of esters. This is also a good reaction for the oxidation of alcohols to esters in terms of time and yields.

Oxidation with aluminium silicate-supported chromic acid.

The preparation of the reagent requires long drying times. The reagent can be kept under vacuum in the dark for several weeks without losing its activity. The capacity of the reagent was found to be 1.1 mmol of chromium trioxide per gram of the dried reagent. 37g of the reagent is required to oxidise 25 mmol of the alcohol in petroleum ether at room temperature. Therefore, 1.6 mmol of chromium trioxide was required to oxidise 1 mmol of the alcohol. The reaction is complete in 24 hours and result in good yields of the ester.

Oxidation with alumina-supported pyridinium chlorochromate.

Although the reagent requires some drying, it is not as time consuming as some of the reagents mentioned above. The reagent can be kept in a vacuum at room temperature in the dark for several weeks without losing its activity. The reagent has a capacity of 1.8 mmol of chlorochromate per gram of the dried solid. 37.5 g of the reagent was required to oxidise 14.7 mmol of the alcohol in hexane at room temperature. Therefore 67.5 mmol of chlorochromate was used to oxidise 14.7 mmol of the alcohol. This implies that on average 4.6 mmol of chlorochromate was used to oxidise 1 mmol of the alcohol. The reaction was complete after 12 hours and resulted in moderate to fair yields of the esters. This reaction is not the best reaction to use in terms of the yields obtained.

Most of the reagents used seem to be good although some work needs to be done on them. However, one can safely say that the use of supported oxidants promises to be one of the best methods in organic synthesis.

A lot of work still needs to be done on supported reagents. The following are some of the factors that should be looked at in future.

- Since the initial aim of this project was to oxidise C₂-C₄ alcohols to their respective aldehydes, an attempt should be made to utilise the above systems to oxidise these alcohol.
- Preparation of these supported oxidants using less chromium.
- The regeneration of the oxidants. So far not much is said in the literature about the regeneration of these valuable oxidants.
- The activity of the reagent after storage for the length of time prescribed in the literature was not validated. In some cases the precise period of storage was not mentioned.
- Work also needs to be done to optimise some of the best reactions.

3. EXPERIMENTAL

3.1. INSTRUMENTATION AND GENERAL PROCEDURES.

NMR spectra were recorded on a Varian T-60 (^1H 60 MHz) and a Gemini 200 (^1H 200 MHz and ^{13}C 50 MHz). All chemical shifts are reported in parts per million (ppm, δ) down-field from Me_4Si (TMS) which is an internal standard, using CDCl_3 as the solvent. Mass spectra were recorded on a Hewlett-Packard gas chromatography mass spectrometer (HP5988A). Infra Red (IR) spectra were recorded on a Shimadzu FTIR-4300 spectrometer using KBr disks.

A balloon was used for reactions performed under an inert atmosphere. Purification of compounds was achieved by fractional distillation. All commercially obtained chemicals were used without further purification. Reactions carried out at 0°C were performed in ice water while those carried out at $12\text{-}15^\circ\text{C}$ were performed in a cold water bath.

In order to keep the content of this thesis as brief as possible, the physical data of the same molecule that was synthesised by different methods has been presented once, in the first method used to synthesise that particular molecule.

3.2 SYNTHESSES

3.2.1. Oxidation of primary alcohols to aldehydes with pyridinium chlorochromate (PCC).

Preparation of PCC.

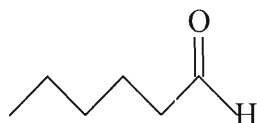
To a stirred solution of 6 M hydrochloric acid (18.4 ml, 0.11 mol) in a 100 ml Erlenmeyer flask was added chromium trioxide (10 g, 0.1 mol), and the mixture stirred for 5 min. at room temperature. The solution was first cooled to 0°C and then warmed to 10°C and pyridine (7.91 g, 0.1 mol) was added dropwise over 10 min. Recooling the solution to 0°C resulted in an orange solid which was collected by filtration. The solid was dried under vacuum for one hour.

General procedure for the oxidation of alcohols with PCC.

To a 250 ml round bottom flask fitted with a reflux condenser and a stirrer bar was added dry dichloromethane (100 ml), PCC (16.2 g, 75 mmol) and 3Å molecular sieves (12.5 g). A solution of the alcohol (50 mmol) in dichloromethane (10 ml) was added to the stirred solution in one portion and the mixture was stirred for 30 min. The reaction mixture was worked up by adding dry ether (100 ml) and the supernatant liquid was decanted from the black gum. The black residue was washed with warm ether (3x25 ml) and the organic layers combined. The organic solution was filtered through a short pad of Florisil and the solvent removed in a rotary evaporator.

Oxidation of 1-hexanol to hexanal with PCC.

1-Hexanol (5.1g, 50 mmol) was used as a substrate for this experiment.



Hexanal

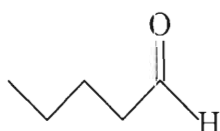
$C_6H_{14}O$

MW=100 g/mol

Yield: 4.0 g (80%). **B. P.:** 131°C/760 mm Hg. **IR:** ν_{\max} 1720 cm^{-1} (C=O). **GC-MS:** m/z (EI) 100 (M^+ , 3%), 82 (32%), 81 (5%), 72 (37%), 57 (74%), 56(100%), 44 (89%), 43 (47%), 41 (55%), 29 (18%), 27 (18%). **NMR** 1H : δ_H (200 MHz) 0.904 [3H, t, CH_3CH_2-]; 1.315 [4H, m, $CH_3CH_2CH_2-$]; 1.641 [2H, m, $-CH_2CH_2CHO$]; 2.429 [2H, t, $-CH_2CHO$]; 9.768 [1H, s, $-CHO$]. ^{13}C : δ_C (50 MHz) 13.88 [d, 1x CH_3 , CH_3CH_2-]; 21.78 [t, 1x CH_2 , CH_3CH_2-]; 22.42 [t, 1x CH_2 , $CH_3CH_2CH_2-$]; 31.33 [t, 1x CH_2 , $CH_3CH_2CH_2CH_2-$]; 43.89 [t, 1x CH_2 , $-CH_2CHO$]; 203.05 [s, $-CHO$].

Oxidation of 1-pentanol to pentanal with PCC.

1-Pentanol (4.4 g, 50 mmol) was used as a substrate for this experiment.



Pentanal

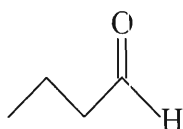
$C_5H_{12}O$

MW=86 g/mol

Yield: 3.1 g (72%). **B. P.:** 103°C/760 mm Hg. **IR:** ν_{\max} 1720 cm^{-1} (C=O). **GC-MS:** m/z (EI) 86 (M^+ , 3%), 58 (32%), 57 (27%), 44 (100%), 41 (44%), 39 (23%), 29 (20%), 27 (12%). **NMR** 1H : δ_H (200 MHz) 0.929 [3H, t, CH_3CH_2-]; 1.344 [2H, m, CH_3CH_2-]; 1.627 [2H, m, $-CH_2CH_2CHO$]; 2.431 [2H, t, $-CH_2CHO$]; 9.769 [1H, s, $-CHO$]. ^{13}C : δ_C (50 MHz) 13.817 [1x CH_3 , d, CH_3CH_2-]; 22.300 [1x CH_2 , t, CH_3CH_2-]; 24.154 [1x CH_2 , t, $CH_3CH_2CH_2-$]; 43.642 [1x CH_2 , t, $-CH_2CHO$]; 203 [s, $-CHO$].

Oxidation of 1-butanol to butanal with PCC.

1-Butanol (3.7 g, 50 mmol) was used as a substrate for this experiment.



Butanal

$C_4H_{10}O$

MW=72 g/mol

Yield: 3.7 g (75%). **B. P.:** 74.8°C/760 mm Hg. **IR:** ν_{\max} 1720 cm^{-1} (C=O). **GC-MS:** m/z (EI) 72 (M+, 2%), 57 (23%), 44 (100%), 41 (56%), 39 (22%), 29 (15%), 27 (7%). **NMR**
 1H : δ_H (200 MHz) 0.968 [3H, t, CH_3CH_2-]; 1.692 [2H, m, CH_3CH_2-]; 2.424 [2H, m, $-CH_2CHO$]; 9.768 [1H, s, $-CHO$]. ^{13}C : δ_C (50 MHz) 13.7 [1x CH_3 , d, CH_3CH_2-]; 15.6 [1x CH_2 , t, CH_3CH_2-]; 45.8 [1x CH_2 , t, $-CH_2CHO$]; 203.1 [s, $-CHO$].

3.2.2. Oxidation of primary alcohols to aldehydes with silica gel-supported pyridinium chromate.

Preparation of silica gel-supported pyridinium chromate.

To a solution of CrO_3 (5 g, 50 mmol) in water (30 ml) was added silica gel (25 g). The excess water was removed on a rotary evaporator to get a yellow free-flowing powder. The resultant solid was placed in a 3-necked round bottom flask and covered with light petroleum (60-80°C) (60 ml). The mixture was cooled to 20°C and pyridine (7.9 g, 0.1 mol) was slowly added with stirring while maintaining the temperature at 20°C. The mixture was then filtered through a sintered glass filter and the solid washed with light petroleum (2x30 ml) and dried by suction to get a dark brown free-flowing powder, which was stored in a brown bottle at room temperature.

Determination of the capacity of the reagent.

0.5 g of the reagent was added to a 0.12 M solution of Fe^{2+} and the mixture was shaken. The excess Fe^{2+} was titrated with 0.02 M solution of dichromate using barium diphenylammonium sulphate as an indicator. The reagent was found to have a capacity of 1.5 mmol per gram of the solid. This method was used to determine the capacity of all the supported reagents used in this project.

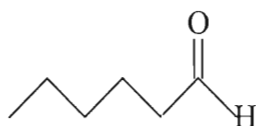
General procedure for the oxidation of primary alcohols to aldehydes.

To a solution of the alcohol (10 mmol) in dichloromethane (30 ml) and acetic acid (0.7 g) was added silica gel-supported pyridinium chromate (29 g) with stirring. The mixture was stirred for 12 h at room temperature (25-27°C). At the end of this period, ether (60 ml) was added and the mixture allowed to stir for another 2 min., filtered and the solid washed with ether (4x36 ml). The combined filtrate was washed successively with 5% HCl (32 ml), water (2x20 ml), 5% NaHCO_3 (32 ml), water (2x32 ml) and brine (20 ml).

The organic layer was then passed through a small bed of alumina which was washed with ether. The excess solvent was removed on a rotary evaporator.

Oxidation of 1-hexanol to hexanal with silica gel-supported pyridinium chromate.

1-Hexanol (1 g, 10 mmol) was used as a substrate for this experiment.



Hexanal

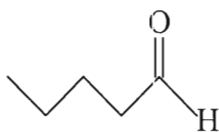
$C_6H_{14}O$

MW=100 g/mol

Yield: 0.93 g (62%)

Oxidation of 1-pentanol to pentanal with silica gel-supported pyridinium chromate.

1-Pentanol (0.8 g, 10 mmol) was used as a substrate for this experiment.



Pentanal

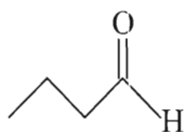
$C_5H_{12}O$

MW=86 g/mol

Yield: 0.8 g (62%)

Oxidation of 1-butanol to butanal with silica gel-supported pyridinium chromate.

1-Butanol (0.6 g, 10 mmol) was used as a substrate for this experiment.



Butanal

$C_4H_{10}O$

MW=72 g/mol

Yield: 0.7 g (65%)

3.2.3. Oxidation of primary alcohols to aldehydes with poly[vinyl(pyridinium chlorochromate)] (PVPCC).

Preparation of PVPCC.

To 10 g of cross-linked poly(vinylpyridine) (PVP) resin suspended in water (20 ml) was added chromium trioxide (9 g, 90 mmol) and conc. HCl (10 ml). The mixture was stirred at room temperature for 1 h and then filtered and the resin washed with distilled water until the filtrate was clear. The orange coloured resin was not dried as it is used in the moist state. The reagent has a capacity of 2 mmol per gram of the solid.

General procedure for the oxidation of primary alcohols to aldehydes.

To a round bottom flask fitted with a magnetic stirrer bar was added PVPCC (10 g) and cyclohexane (40 ml). The alcohol (17 mmol) was added with stirring to the heterogeneous mixture and the mixture was allowed to stir until all of the alcohol was used up (monitored by GC-MS). The reaction mixture was then filtered and the resin washed with dichloromethane. The removal of the solvent on the rotary evaporator resulted in the aldehyde.

Oxidation of 1-hexanol to hexanal with PVPCC.

1-Hexanol (1.7 g, 17 mmol) was used as a substrate for this experiment.



Hexanal

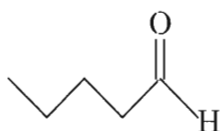
$C_6H_{14}O$

MW=100 g/mol

Yield: 1.2 g (71%)

Oxidation of 1-pentanol to pentanal with PVPCC.

1-Pentanol (1.5 g, 17 mmol) was used as a substrate for this experiment.



Pentanal

$C_5H_{12}O$

MW=86 g/mol

Yield: 1.1 g, (75%)

3.2.4. Oxidation of primary alcohols to aldehydes with silica gel-supported chromium trioxide

Preparation of silica gel supported chromium trioxide.

The reagent was prepared by co-grinding anhydrous chromium trioxide (2 g, 20 mmol) and silica gel (8 g). The yellow free flowing powder was then activated at 100°C for 4 h 30 min. The reagent attained a brown colour. The reagent has a capacity of 1.8 mmol per gram of the solid.

General procedure for the oxidation of primary alcohols to aldehydes.

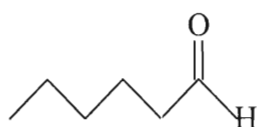
To a round bottom flask fitted with a magnetic stirrer bar was added dichloromethane (100 ml). Silica gel-supported chromium trioxide (10 g, 100 mmol) was added with stirring at 15°C. The alcohol (20 mmol) was added dropwise and the mixture was stirred until no alcohol was present (GC-MS). The mixture was then filtered through a sintered glass filter and the residue washed thoroughly with warm dichloromethane. The excess solvent was removed through the rotary evaporator to afford the aldehyde.

General procedure for the oxidation of alcohols to esters.

To a round bottom flask fitted with a magnetic stirrer bar was added dichloromethane (100 ml). To this was added silica gel-supported chromium trioxide (10 g, 100 mmol) with stirring at 25°C. The alcohol (20 mmol) was added dropwise and the mixture was allowed to stir until no alcohol was present (GC-MS). The mixture was then filtered and washed thoroughly with hot dichloromethane. Removal of the solvent afforded the ester.

Oxidation of 1-hexanol to hexanal with silica gel supported chromium trioxide.

1-Hexanol (2 g, 20 mmol) was used as a substrate for this experiment.



Hexanal

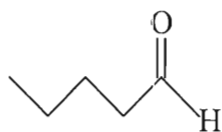
$C_6H_{14}O$

MW=100 g/mol

Yield: 1,6 g (80%)

Oxidation of 1-pentanol to pentanal with silica gel supported chromium trioxide.

1-Pentanol (1.8 g, 20 mmol) was used as a substrate for this experiment.



Pentanal

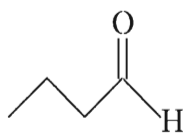
$C_5H_{12}O$

MW=86 g/mol

Yield: 1.4 g (81%)

Oxidation of 1-butanol to butanal with silica gel supported chromium trioxide.

1-Butanol (1.5 g, 20 mmol) was used as a substrate for this experiment.



Butanal

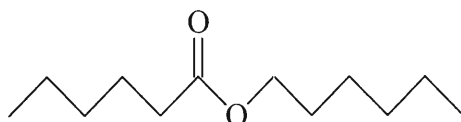
$C_4H_{10}O$

MW=72 g/mol

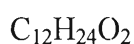
Yield: 1.1 g (76%)

Oxidation of 1-hexanol to hexyl hexanoate with silica gel-supported chromium trioxide.

1-Hexanol (2 g, 20 mmol) was used as a substrate for this experiment.



Hexyl hexanoate

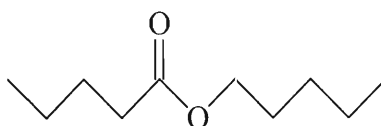


MW=200 g/mol

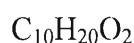
Yield: 2.6 g (65%). **B. P.:** 246°C/760 mm Hg. **IR:** ν_{max} 1735 cm^{-1} (C=O). **GC-MS:** m/z (EI) 200 (M^+ , 3%), 144 (5%), 117 (100%), 99 (78%), 84 (78%), 71 (27%), 69 (34%), 56 (53%), 43 (66%), 29 (13%). **NMR** ^1H : δ_{H} (200 MHz) 0.896 [6H, t, CH_3CH_2 -]; 1.322 [10H, m, $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{OCH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$]; 1.625 [4H, m, $-\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{OCH}_2\text{CH}_2$ -]; 2.294 [2H, t, $-\text{CH}_2\text{C}(\text{O})\text{O}$ -]; 4.061 [2H, t, $-\text{C}(\text{O})\text{OCH}_2$ -]. ^{13}C : δ_{C} (50 MHz) 13.9 [d, 1 \times CH₃, CH_3CH_2 -]; 14.0 [t, 1 \times CH₃, $-\text{CH}_2\text{CH}_3$]; 22.3 [t, 1 \times CH₂, CH_3CH_2 -]; 22.5 [t, 1 \times CH₂, $-\text{CH}_2\text{CH}_3$]; 24.7 [t, 1 \times CH₂, $-\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{O}$ -]; 25.6 [t, 1 \times CH₂, $-\text{C}(\text{O})\text{OCH}_2\text{CH}_2\text{CH}_2$ -]; 28.6 [t, 1 \times CH₂, $-\text{C}(\text{O})\text{OCH}_2\text{CH}_2$ -]; 31.3 [t, 1 \times CH₂, $-\text{CH}_2\text{CH}_2\text{CH}_3$]; 31.4 [t, 1 \times CH₂, $\text{CH}_3\text{CH}_2\text{CH}_2$ -]; 34.4 [t, 1 \times CH₂, $-\text{CH}_2\text{C}(\text{O})\text{O}$ -]; 64.4 [t, 1 \times CH₂, $-\text{C}(\text{O})\text{OCH}_2$ -]; 174.0 [s, $-\text{C}(\text{O})\text{O}$ -]

Oxidation of 1-pentanol to pentyl pentanoate with silica gel-supported chromium trioxide.

1-Pentanol (1.8 g, 20 mmol) was used as a substrate for this experiment.



Pentyl pentanoate

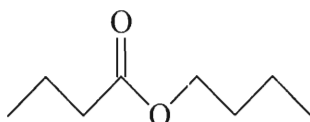


MW=172 g/mol

Yield: 2.6 g (75%). **B. P.:** 203.7°C/760 mm Hg. **IR:** ν_{max} 1735 cm^{-1} (C=O). **GC-MS:** m/z (EI) 172 (M^+ , 2%), 143 (3%), 130 (8%), 103 (100%), 85 (55%), 70 (45%), 57(16%), 55 (11%), 43 (8%), 41 (3%) 29 (3%). **NMR** ^1H : δ_{H} (200 MHz) 0.882 [6H, t, CH_3CH_2 -]; 1.325 [6H, m, $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{OCH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$]; 1.615 [4H, m, $-\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{OCH}_2\text{CH}_2$ -]; 2.302 [2H, t, $-\text{CH}_2\text{C}(\text{O})\text{O}$ -]; 4.060 [2H, t, $-\text{C}(\text{O})\text{OCH}_2$ -]. ^{13}C : δ_{C} (50MHz) 13.951 [d, 1x CH_3 , CH_3CH_2 -]; 14.082 [d, 1x CH_3 , $-\text{CH}_2\text{CH}_3$]; 22.356 [t, 1x CH_2 , CH_3CH_2 -]; 22.575 [t, 1x CH_2 , $-\text{CH}_2\text{CH}_3$]; 27.323 [t, 1x CH_2 , $\text{CH}_3\text{CH}_2\text{CH}_2$ -]; 28.639 [t, 1x CH_2 , $-\text{C}(\text{O})\text{OCH}_2\text{CH}_2$ -]; 28.770 [t, 1x CH_2 , $-\text{CH}_2\text{CH}_2\text{CH}_3$]; 33.989 [t, 1x CH_2 , $-\text{CH}_2\text{C}(\text{O})\text{O}$ -]; 64.412 [t, 1x CH_2 , $-\text{C}(\text{O})\text{OCH}_2$ -]; 174.045 [s, $-\text{C}(\text{O})\text{O}$].

Oxidation of 1-butanol to butyl butanoate with silica gel-supported chromium trioxide.

1-Butanol (1.5 g, 20 mmol) was used as a substrate for this experiment.



Butyl butanoate

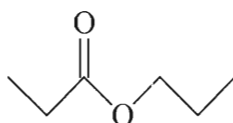


MW=144 g/mol

Yield: 1.7 g (60%). **B. P.:** 166°C/760 mm Hg. **IR:** ν_{max} 1735 cm^{-1} (C=O). **GC-MS:** m/z (EI) 144 (M^+ , 1%), 116 (5%), 101 (13%), 89 (87%), 71 (100%), 56 (37%), 43 (21%), 41 (13%), 29 (5%), 27 (5%). **NMR** ^1H : δ_{H} (200 MHz) 0.948 [6H, m, CH_3CH_2 -]; 1.194 [4H, m, $\text{CH}_3\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{OCH}_2\text{CH}_2\text{CH}_2\text{CH}_3$]; 1.599 [2H, m, $-\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{O}-$]; 2.243 [2H, t, $-\text{CH}_2\text{C}(\text{O})\text{O}-$]; 4.074 [2H, t, $-\text{C}(\text{O})\text{OCH}_2$ -]. ^{13}C : δ_{C} (50 MHz) 13.9 [d, 1x CH_3 , $-\text{CH}_2\text{CH}_3$]; 14.1 [d, 1x CH_3 , CH_3CH_2 -]; 20.9 [t, 1x CH_2 , $-\text{CH}_2\text{CH}_3$]; 21.5 [t, 1x CH_2 , CH_3CH_2 -]; 30.8 [t, 1x CH_2 , $\text{CH}_3\text{CH}_2\text{CH}_2$ -]; 36.8 [t, 1x CH_2 , $-\text{CH}_2\text{C}(\text{O})\text{O}-$]; 64.3 [t, 1x CH_2 , $-\text{C}(\text{O})\text{OCH}_2$ -]; 173.3 [s, $-\text{C}(\text{O})\text{O}-$].

Oxidation of 1-propanol to propyl propanoate with silica gel-support chromium trioxide.

1-Propanol (1.2 g, 20 mmol) was used as a substrate for this experiment.



Propyl propanoate

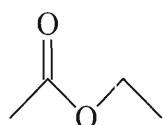


MW=116 g/mol

Yield: 0.8 g (65%). **B. P.:** 122°C/760 mm Hg. **IR:** ν_{max} 1735 cm^{-1} (C=O). **GC-MS:** m/z (EI) 116 (M⁺, 2%), 87 (10%), 75 (45%), 57 (76%), 43 (41%), 41 (26%), 31 (14%), 29 (100%), 26 (11%). **NMR** ¹H: δ_{H} (200 MHz) 0.978 [6H, t, CH₃CH₂-]; 1.123 [2H, m, -CH₂CH₃]; 2.244 [2H, t, -CH₂C(O)O-]; 4.013 [2H, t, -C(O)OCH₂-]. ¹³C: δ_{C} 9.8 [d, 1xCH₃, CH₃CH₂-]; 10.4 [d, 1xCH₃, -CH₂CH₃]; 23.5 [t, 1xCH₂, -CH₂CH₃]; 28.1 [t, 1xCH₂, -CH₂C(O)O-]; 65.9 [t, 1xCH₂, C(O)OCH₂-]; 174.2 [s, -C(O)O-].

Oxidation of ethanol to ethyl ethanoate with silica gel-supported chromium trioxide.

Ethanol (0.9 g, 20 mmol) was used as a substrate in this experiment.



Ethyl ethanoate

C₄H₈O₂

MW=88 g/mol

Yield: 0.8 g (45%), **B. P.:** 77°C/760 mm Hg. **IR:** ν_{\max} 1735cm⁻¹ (C=O). **GC-MS:** *m/z* (EI) 88 (M⁺, 10%), 73 (11%), 70 (10%), 61 (28%), 45 (32%), 43 (100%), 42 (18%), 29 (46%), 27 (15%). **NMR** ¹H: δ_{H} (200 MHz) 1.261 [3H, t, CH₃CH₂-]; 2.046 [3H, s, CH₃C(O)O-]; 4.114 [2H, q, -CH₂CH₃]. ¹³C: δ_{C} (50 MHz) 14.221 [d, 1xCH₃, -CH₂CH₃]; 21.054 [t, 1xCH₃, CH₃C(O)O-]; 60.410 [d, 1xCH₂, -CH₂CH₃]; 171.148 [s, -C(O)O-].

3.2.5. Oxidation of primary alcohols to aldehydes with chromium trioxide.

General procedure for the oxidation of primary alcohols to aldehydes

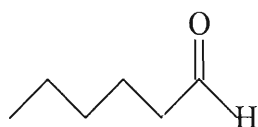
Chromium trioxide (7.5 g, 75 mmol) was added to a cooled mixture (0°C) of celite (7.5 g) and the alcohol (50 mmol) in dichloromethane (112.5 ml) and diethyl ether (37.5 ml) over 15 min. When all the alcohol had reacted diethyl ether (75 ml) and celite (2.5 g) were added to the reaction mixture and the reaction was left to stir for 15 min. The mixture was then filtered through a sintered glass filter and the solid washed thoroughly with ether. The solvent was removed by a rotary evaporator.

General procedure for the oxidation of alcohols to esters.

Chromium trioxide (7.5 g, 75 mmol) was added to a mixture of celite (7.5 g) and the alcohol (50 mmol) in dichloromethane (112.5 ml) and diethyl ether (37.5 ml) over 15 min. at room temperature. Diethyl ether (75 ml) and celite (2.5 g) were added to the reaction mixture when all the alcohol had reacted (monitored by GC-MS). The reaction was allowed to stir for a further 15 min and then filtered through a sintered glass filter and the solid washed with ether. The removal of the solvent afforded the ester.

Oxidation of 1-hexanol to hexanal with chromium trioxide.

1-Hexanol (5.1 g, 50 mmol) was used as a substrate for this experiment.



Hexanal

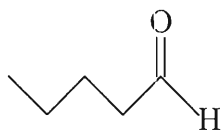
$C_6H_{14}O$

MW=100 g/mol

Yield: 3.3 g (66%)

Oxidation of 1-pentanol to pentanal with chromium trioxide system.

1-Pentanol (4.4 g, 50mmol) was used as a substrate for this experiment.



Pentanal

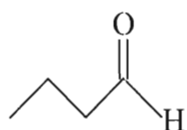
$C_5H_{12}O$

MW=86 g/mol

Yield: 2.2 g (51%)

Oxidation of 1-butanol to butanal with chromium trioxide system.

1-Butanol (3.7 g, 50 mmol) was used as a substrate for this experiment.



Butanal

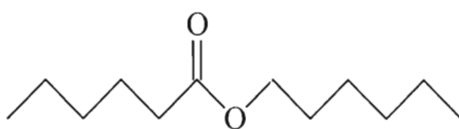
$C_4H_{10}O$

MW=72 g/mol

Yield: 1.9 g (53%)

Oxidation of 1-hexanol to hexyl hexanoate with chromium trioxide.

1-Hexanol (5.1 g, 50 mmol) was used as a substrate for this experiment.



Hexyl hexanoate

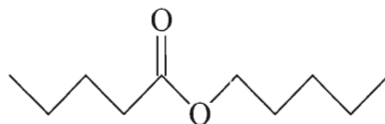
$C_{12}H_{24}O_2$

MW=200 g/mol

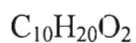
Yield: 6 g (60%)

Oxidation of 1-pentanol to pentyl pentanoate with chromium trioxide.

1-Pentanol (4.4 g, 50 mmol) was used as a substrate in this experiment.



Pentyl pentanoate

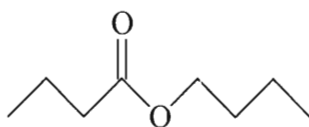


MW=172 g/mol

Yield: 5.2 g (60%)

Oxidation of 1-butanol to butyl butanoate with chromium trioxide.

1-Butanol (3.7 g, 50 mmol) was used as a substrate for this experiment.



Butyl butanoate

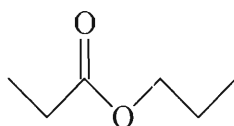


MW=144 g/mol

Yield: 4.2 g (58%)

Oxidation of 1-propanol to propyl propanoate with chromium trioxide.

1-Propanol (3 g, 50 mmol) was used as a substrate for this experiment.



Propyl propanoate

$C_6H_{12}O_2$

MW=116 g/mol

Yield: 2.9 (50%)

3.2.6. Oxidation of primary alcohols to esters with alumina-supported chromium trioxide.

Preparation of alumina-supported chromium trioxide.

“Wet”-alumina (30 g) was prepared by adding distilled water (5 g) to neutral alumina (25 g) in portions followed by vigorous stirring of the mixture on every addition. To this mixture was added pulverised chromium trioxide (6 g, 60 mmol) and the mixture was stirred until a uniform orange colour was achieved. The chromium trioxide/alumina mixture was added to hexane (100 ml) and allowed to stir for 10 min. The solid was then filtered and dried by suction to result in a brown free-flowing powder. The reagent was found to have a capacity of 2.1 mmol per gram of the solid.

General procedure for the oxidation of primary alcohols to symmetrical esters.

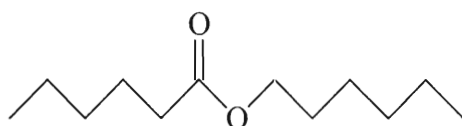
To a round bottom flask fitted with a magnetic stirrer bar was added hexane (100 ml). Alumina-supported chromium trioxide (15 g) was added with stirring. Alcohol (10 mmol) was added and the heterogeneous mixture was allowed to stir for 24 h at room temperature. The solid was then filtered and washed with diethyl ether. The solvent was removed with a rotary evaporator to afford the ester.

Synthesis of asymmetrical esters from hexanal and different alcohols.

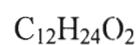
To a round bottom flask fitted with a magnetic stirrer bar was added hexane (100 ml). Alumina-supported chromium trioxide (15 g) was added with stirring. Hexanal (5 mmol) and an alcohol (5 mmol) were added and the heterogeneous mixture was allowed to stir for 24 h at room temperature. The solid was then filtered and washed with diethyl ether. The solvent was removed with a rotary evaporator to afford the ester.

Oxidation of 1-hexanol to hexyl hexanoate with alumina-supported chromium trioxide.

1-Hexanol (1 g, 10 mmol) was used as a substrate for this experiment.



Hexyl hexanoate

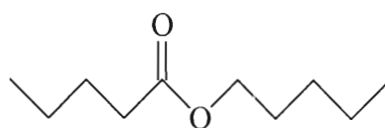


MW=200 g/mol

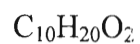
Yield: 1.5 g (75%)

Oxidation of 1-pentanol to pentyl pentanoate with alumina-supported chromium trioxide.

1-Pentanol (0.9 g, 10 mmol) was used as a substrate for this experiment.



Pentyl pentanoate

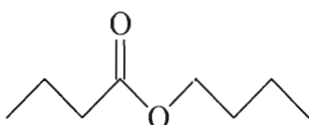


MW=172 g/mol

Yield: 1.2 g (72%)

Oxidation of 1-butanol to butyl butanoate with alumina-supported chromium trioxide.

1-Butanol (0.7 g, 10 mmol) was used as a substrate for this experiment.



Butyl butanoate

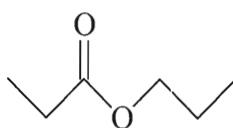


MW=144 g/mol

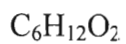
Yield: 0.9 g (65%)

Oxidation of 1-propanol to propyl propanoate with alumina-supported chromium trioxide.

1-Propanol (0.6 g, 10 mmol) was used as a substrate for this experiment.



Propyl propanoate

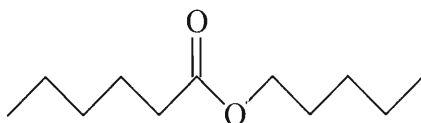


MW=116 g/mol

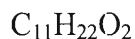
Yield: 0.8 g (70%)

Synthesis of pentyl hexanoate from hexanal and 1-pentanol with alumina-supported chromium trioxide.

Hexanal (0.5 g, 5 mmol) and 1-pentanol (0.45 g, 5 mmol) were used for this synthesis.



Pentyl hexanoate

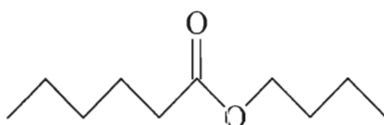


MW=186 g/mol

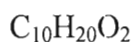
Yield: 1.4 g (77). **B. P.:** 226°C/760 mm Hg. **IR:** ν_{max} 1735 cm^{-1} (C=O). **GC-MS:** m/z (EI) 186(M^+ , 3%), 130 (6%), 117 (100%), 99 (66%), 71 (32%), 70 (95%), 60 (16%), 55 (24%), 43 (47%), 41 (26%), 29 (16%), 28 (24%). **NMR** ^1H : δ_{H} (200 MHz) 0.899 [6H, t, CH_3CH_2 -]; 1.357 [8H, m, $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{OCH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$]; 1.644 [4H, m, $-\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{OCH}_2\text{CH}_2$ -]; 2.3267 [2H, t, $-\text{CH}_2\text{C}(\text{O})\text{O}$ -]; 4.059 [2H, t, $-\text{C}(\text{O})\text{OCH}_2$ -]. ^{13}C : δ_{C} (50 MHz) 13.9 [d, 1x CH_3 , CH_3CH_2 -]; 14.1 [d, 1x CH_3 , $-\text{CH}_2\text{CH}_3$]; 22.0 [t, 1x CH_2 , $-\text{CH}_2\text{CH}_3$]; 22.3 [t, 1x CH_2 , CH_3CH_2 -]; 24.4 [t, 1x CH_2 , $-\text{C}(\text{O})\text{OCH}_2\text{CH}_2$ -]; 28.0 [t, 1x CH_2 , $-\text{C}(\text{O})\text{OCH}_2\text{CH}_2\text{CH}_2$ -]; 27.9 [t, 1x CH_2 , $-\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{O}$ -]; 31.8 [t, 1x CH_2 , $\text{CH}_3\text{CH}_2\text{CH}_2$ -]; 34.8 [t, 1x CH_2 , $-\text{CH}_2\text{C}(\text{O})\text{O}$ -]; 64.3 [t, 1x CH_2 , $-\text{C}(\text{O})\text{OCH}_2$ -]; 17.9 [s, $-\text{C}(\text{O})\text{O}$ -].

Synthesis of butyl hexanoate from hexanal and 1-butanol with alumina-supported chromium trioxide.

Hexanal (0.5 g, 5 mmol) and 1-butanol (0.37 g, 5 mmol) were used for this synthesis.



Butyl hexanoate

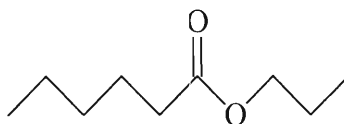


MW=172 g/mol

Yield: 1.5 g (85%). **B. P.:** 208°C/760 mm Hg. **IR:** ν_{max} 1735 cm^{-1} (C=O). **GC-MS:** m/z (EI) 172 (M^+ , 3%), 143 (3%), 117 (100%), 99 (79%), 71 (21%), 60 (24%), 56 (63%), 43 (29%), 41 (24%), 29 (16%). **NMR** ^1H : δ_{H} (200 MHz) 0.899 [6H, t, CH_3CH_2 -], 1.356 [8H, m, $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{OCH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3$], 1.623 [4H, m, $\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{OCH}_2\text{CH}_2$ -], 2.299 [2H, t, $-\text{CH}_2\text{C}(\text{O})\text{O}$ -], 4.089 [2H, t, $-\text{C}(\text{O})\text{OCH}_2$ -]. ^{13}C : δ_{C} (50 MHz) 13.8 [d, 1x CH_3 , CH_3CH_2 -]; 13.9 [d, 1x CH_3 , $-\text{CH}_2\text{CH}_3$]; 22.1 [t, 1x CH_2 , CH_3CH_2 -]; 19.8 [t, 1x CH_2 , $-\text{CH}_2\text{CH}_3$]; 24.4 [t, 1x CH_2 , $-\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{O}$ -]; 31.9 [t, 1x CH_2 , $-\text{C}(\text{O})\text{OCH}_2\text{CH}_2$ -]; 32.1 [t, 1x CH_2 , $\text{CH}_3\text{CH}_2\text{CH}_2$ -]; 34.7 [t, 1x CH_2 , $-\text{CH}_2\text{C}(\text{O})\text{O}$ -]; 64.1 [t, 1x CH_2 , $-\text{C}(\text{O})\text{CH}_2$ -]; 174.0 [s, $-\text{C}(\text{O})\text{O}$ -].

Synthesis of propyl hexanoate from hexanal and 1-propanol with alumina-supported chromium trioxide.

Hexanal (0.5 g, 5 mmol) and propanol (0.3 g, 5 mmol) were used for this synthesis.



Propyl hexanoate



MW= 158 g/mol

Yield: 1.3 g (80%). **B. P.:** 187°C/760 mm Hg. **IR:** ν_{max} 1735 cm^{-1} (C=O). **GC-MS:** m/z (EI) 158 (M^+ , 3%), 129 (5%), 117 (89%), 99 (100%), 87 (18%), 73 (29%), 71 (26%), 61 (55%), 60 (50%), 43 (68%), 41 (34%), 29 (18%). **NMR** ^1H : δ_{H} (200 MHz) 1.889 [6H, t, CH_3CH_2 -]; 1.299 [4H, m, $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{O}$ -]; 1.6.90 [4H, m, $-\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{OCH}_2\text{CH}_2$ -]; 2.355 [2H, m, $-\text{CH}_2\text{C}(\text{O})\text{O}$ -]; 4.060 [2H, t, $-\text{C}(\text{O})\text{OCH}_2$ -]. ^{13}C : δ_{C} (50 MHz) 14.1 [d, 1x CH_3 , CH_3CH_2 -]; 10.1 [d, 1x CH_3 , $-\text{CH}_2\text{CH}_3$]; 21.9 [t, 1x CH_2 , CH_3CH_2 -]; 22.0 [t, 1x CH_2 , $-\text{CH}_2\text{CH}_3$]; 24.2 [t, 1x CH_2 , $-\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{O}$ -]; 31.7 [t, 1x CH_2 , $\text{CH}_3\text{CH}_2\text{CH}_2$ -]; 34.0 [t, 1x CH_2 , $-\text{CH}_2\text{C}(\text{O})\text{O}$ -]; 65.9 [t, 1x CH_2 , $-\text{C}(\text{O})\text{OCH}_2$ -]; 173.8 [s, $-\text{C}(\text{O})\text{O}$ -].

3.2.7. Oxidation of primary alcohols to esters with kieselguhr-supported chromic acid.

Preparation of kieselguhr-supported chromic acid.

To a solution of chromic anhydride (10 g, 100 mmol) in water (30 ml) was added kieselguhr (20 g) with stirring. Excess water was evaporated *in vacuo* and the solid dried at 100°C for 4h to give a yellow solid. The reagent has 1 mmol per gram of the dried solid.

General procedure for the oxidation of primary alcohols to symmetrical esters.

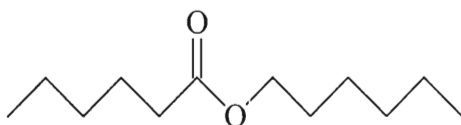
To a round bottom flask fitted with a magnetic stirrer bar was added petroleum ether (24 ml). Kieselguhr-supported chromic acid (18 g) was added with stirring. To this heterogeneous mixture was added a solution of alcohol (20 mmol) in petroleum ether (60-80°) (8 ml) and the mixture was allowed to stir for 1 h. The solid is then filtered and washed with petroleum ether (3x30 ml). The evaporation of the solvent yielded the ester.

Synthesis of asymmetrical esters from hexanal and different alcohols.

To a round bottom flask fitted with a magnetic stirrer bar was added petroleum ether (60-80°C) (24 ml). Kieselguhr-supported chromic acid (18 g) was added with stirring. To this heterogeneous mixture was added a solution of hexanal (10 mmol) and an alcohol (10 mmol) in petroleum ether (8 ml) and the mixture was allowed to stir for 1h. The solid was filtered and washed with petroleum ether (3x30 ml). Evaporation of the solvent yielded the ester.

Oxidation of 1-hexanol to hexyl hexanoate with kieselguhr-supported chromic acid.

1-Hexanol (2.g, 20 mmol) was used as a substrate in this experiment.



Hexyl hexanoate

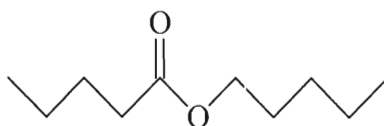
$C_{12}H_{24}O_2$

MW=200 g/mol

Yield: 3.4 g (85%)

Oxidation of 1-pentanol to pentyl pentanoate with kieselguhr-supported chromic acid.

1-Pentanol (1.8 g, 20 mmol) was used as a substrate in this experiment.



Pentyl pentanoate

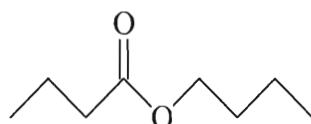
$C_{10}H_{20}O_2$

MW=172 g/mol

Yield: 2.9 g (86%)

Oxidation of 1-butanol to butyl butanoate with kieselguhr-supported chromic acid.

1-Butanol (1.5 g, 20 mmol) was used as a substrate in this experiment.



Butyl butanoate

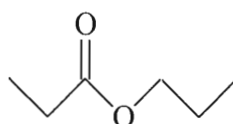


MW=144 g/mol

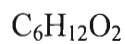
Yield: 1.7 g (60%)

Oxidation of 1-propanol to propyl propanoate with kieselguhr-supported chromic acid.

1-Propanol (1.2 g, 20 mmol) was used as a substrate for this experiment.



Propyl propanoate

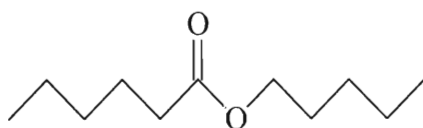


MW=116 g/mol

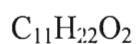
Yield: 0.9 g (40%)

Synthesis of pentyl hexanoate from hexanal and 1-pentanol with kieselguhr-supported chromic acid.

Hexanal (1 g, 10 mmol) and 1-pentanol (0.9 g, 10 mmol) were used for this experiment.



Pentyl hexanoate

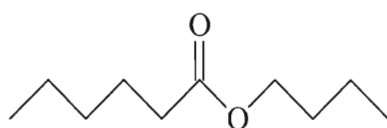


MW=186 g/mol

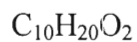
Yield: 2.9 g (77%)

Synthesis of butyl hexanoate from hexanal and butanol with kieselguhr-supported chromic acid.

Hexanal (1 g, 10 mmol) and butanol (0.8 g, 10 mmol) were used for this synthesis.



Butyl hexanoate

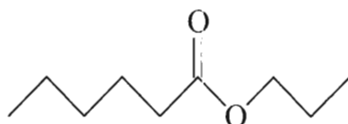


MW=172 g/mol

Yield: 2.7 g, (80%)

Synthesis of propyl hexanoate from hexanal and 1-propanol with kieselguhr-supported chromic acid.

Hexanal (1 g, 10 mmol) and 1-propanol (0.6 g, 10 mmol) were used for this synthesis.



Propyl hexanoate

$C_9H_{18}O_2$

MW= 158 g/mol

Yield: 2.5 g, (79%)

3.2.8. Oxidation of primary alcohols to esters with aluminium silicate-supported chromic acid.

Preparation of aluminium silicate-supported chromic acid.

To a solution of chromium trioxide (5 g, 50 mmol) in water (50 ml) was added aluminium silicate (20 g) with stirring. Excess water was removed and the resultant yellow solid was dried at 100°C for 6 h. The reagent has a capacity of 1.1 mmol per gram of the dried solid.

General procedure for the oxidation of primary alcohols to symmetrical esters.

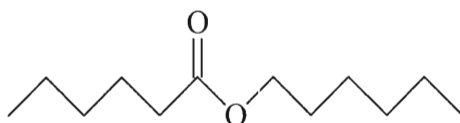
To a round bottom flask fitted with a magnetic stirrer bar was added petroleum ether (60-80°) (45 ml). Aluminium silicate-supported chromic acid (37 g) was added with stirring. To this mixture was added a solution of the alcohol (25 mmol) in petroleum ether (5 ml). The mixture was allowed to stir until no alcohol was present. The progress of the reaction was monitored by GC-MS. The solid was then filtered and washed with petroleum ether (3x10 ml). Evaporation of the solvent resulted in the ester.

Synthesis of asymmetrical esters with hexanal and different alcohols with aluminium silicate-supported chromic acid.

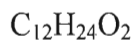
To a round bottom flask fitted with a magnetic stirrer bar was added petroleum ether (60-80°C) (45 ml). Aluminium silicate-supported chromic acid (37 g) was added with stirring. To this mixture was added a solution of hexanal (12.5 mmol) and an alcohol (12.5 mmol) in petroleum ether (5 ml). The mixture was allowed to stir until no alcohol or aldehyde was present. The progress of the reaction was monitored by GC-MS. The solid was then filtered and washed with petroleum ether (3x30ml). Evaporation of the solvent resulted in the ester.

Oxidation of 1-hexanol to hexyl hexanoate with aluminium silicate-supported chromic acid.

1-Hexanol (2.6 g, 25 mmol) was used as a substrate in this experiment.



Hexyl hexanoate

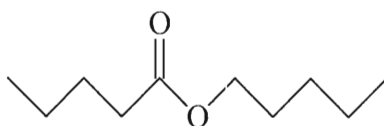


MW=200 g/mol

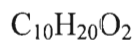
Yield: 3.1 g (63%)

Oxidation of 1-pentanol to pentyl pentanoate with aluminium silicate-supported chromic acid.

1-Pentanol (2.2 g, 25 mmol) was used as a substrate for this experiment.



Pentyl pentanoate

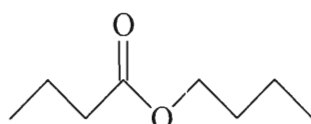


MW=172 g/mol

Yield: 2.9 g (69%)

Oxidation of 1-butanol to butyl butanoate with aluminium silicate-supported chromic acid.

1-Butanol (1.8 g, 25 mmol) was used as a substrate in this experiment.



Butyl butanoate

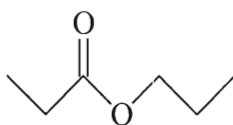


MW=144 g/mol

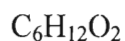
Yield: 1.8 g (50%)

Oxidation of 1-propanol to propyl propanoate with aluminium silicate-supported chromic acid.

1-Propanol (1.5 g, 25 mmol) was used as a substrate for this experiment.



Propyl propanoate

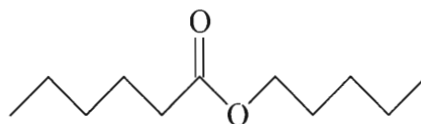


MW=116 g/mol

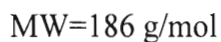
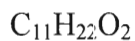
Yield: 1.4 g (49%)

Synthesis of pentyl hexanoate from hexanal and 1-pentanol with aluminium silicate-supported chromic acid.

Hexanal (1.3 g, 12.5 mmol) and 1-pentanol (1.1 g, 12.5 mmol) were used for this synthesis.



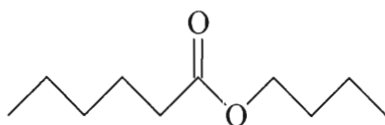
Pentyl hexanoate



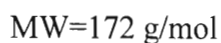
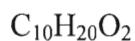
Yield: 3.7 g (80%)

Synthesis of butyl hexanoate from hexanal and 1-butanol with aluminium silicate-supported chromic acid.

Hexanal (1.3 g, 12.5 mmol) and 1-butanol (0.9 g, 12.5 mmol) were used for this synthesis.



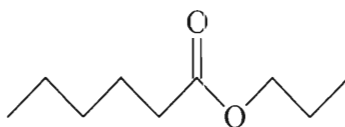
Butyl hexanoate



Yield: 3.2 g, (75%)

Synthesis of propyl hexanoate from hexanal and 1-propanol with aluminium silicate-supported chromic acid.

Hexanal (1.3 g, 12.5 mmol) and 1-propanol (0.8 g, 12.5 mmol) were used for this synthesis.



Propyl hexanoate

$C_9H_{18}O_2$

MW= 158 g/mol

Yield: 2.4 g, (60%)

3.2.9. Oxidation of primary alcohols to esters with alumina-supported pyridinium chlorochromate.

Preparation of aluminium-supported PCC.

To a solution of chromium trioxide (6 g, 60 mmol) in 6M HCl (11 ml) was added pyridine (4.8 g) within 10 min at 40°C. The mixture was kept at 0°C until a yellow solid forms. Reheating to 40°C resulted in a solution. Alumina (50 g) was then added to the solution with stirring at 40°C. Removal of the excess liquid resulted in an orange solid which was dried in vacuum for 2 h at room temperature. The reagent has a capacity of 1.8 mmol per gram of the dried solid.

General procedure for the oxidation of alcohols to symmetrical esters.

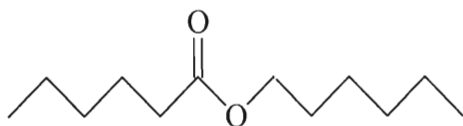
To a flask containing a solution of the alcohol (14.7 mmol) in hexane (50 ml) was added aluminium-supported PCC (37.5 g) with stirring. When no more alcohol was present, the solid was filtered and washed with ether (3x50 ml). Evaporation of the solvent afforded the ester.

General procedure for the synthesis of asymmetrical esters from hexanal and different alcohols.

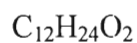
To a flask containing a solution of hexanal (7.4 mmol) and an alcohol (7.4 mmol) in hexane (50 ml) was added alumina-supported PCC (37.5 g) with stirring. The reaction was stirred until all the aldehyde and alcohol had reacted. The progress of the reaction was monitored by GC-MS. The solid was then filtered and washed with ether (3x50 ml). Evaporation of the solvent afforded the ester.

Oxidation of 1-hexanol to hexyl hexanoate with alumina-supported PCC.

1-Hexanol (1.5 g, 14.7 mmol) was used as a substrate for this experiment.



Hexyl hexanoate

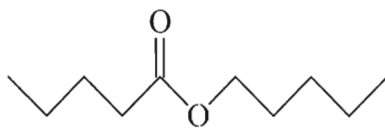


MW=200 g/mol

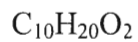
Yield: 1.5 g (51%)

Oxidation of 1-pentanol to pentyl pentanoate with alumina-supported PCC.

1-Pentanol (1.3 g, 14.7 mmol) was used as a substrate for this experiment.



Pentyl pentanoate

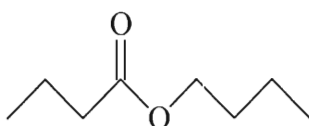


MW=172 g/mol

Yield: 1.1 g (45%)

Oxidation of 1-butanol to butyl butanoate with alumina-supported PCC.

1-Butanol (1.1 g, 14.7 mmol) was used as a substrate for this experiment.



Butyl butanoate

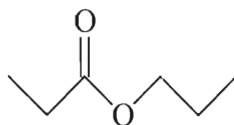
$C_8H_{16}O_2$

MW=144 g/mol

Yield: 0.7 g (32%)

Oxidation of 1-propanol to propyl propanoate with alumina-supported PCC.

1-Propanol (0.9 g, 14.7 mmol) was used as a substrate for this experiment.



Propyl propanoate

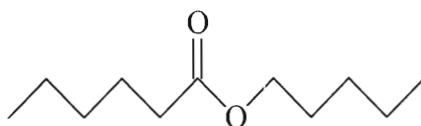
$C_6H_{12}O_2$

MW=116 g/mol

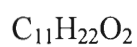
Yield: 0.6 g (35%)

Synthesis of pentyl hexanoate from hexanal and 1-pentanol with alumina-supported PCC.

Hexanal (0.8 g, 7.4 mmol) and 1-pentanol (0.7 g, 7.4 mmol) were used for this synthesis.



Pentyl hexanoate

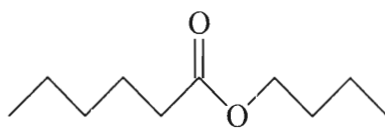


MW=186 g/mol

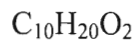
Yield: 1.9 g, (70%)

Synthesis of butyl hexanoate from hexanal and 1-butanol with alumina-supported PCC.

Hexanal (0.8 g, 7.4 mmol) and 1-butanol (0.6 g, 7.4 mmol) were used for this synthesis.



Butyl hexanoate

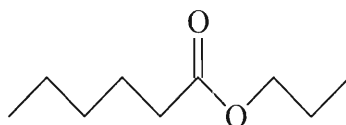


MW=172 g/mol

Yield: 1.6 g, (65%)

Synthesis of propyl hexanoate from hexanal and 1-propanol with alumina-supported PCC.

Hexanal (0.8 g, 7.4 mmol) and 1-propanol (0.5 g, 7.4 mmol) were used for this synthesis.



Propyl hexanoate

$C_9H_{18}O_2$

MW= 158 g/mol

Yield: 1.5g, (66%)

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5. APPENDIX

^1H and ^{13}C NMR

