Marta Pastor Fernandes Arraios Faria

Bachelor Degree in Chemical and Biochemical Engineering

Catalytic Valorization of Malic Acid with Alternative Solvents

Dissertation submitted in partial fulfillment

of the requirements for the degree of

Master of Science in

Chemical and Biochemical Engineering

Adviser: Ewa Bogel-Lukasik, Auxiliary Researcher,

Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa

FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

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Abstract

The main focus of this research project consisted on the catalytic hydrogenation of malic acid, using ionic liquids as solvents and in presence of supercritical CO_2. The catalysts used in this project were ruthenium and palladium heterogeneous catalysts.

Using the catalyst ruthenium (II) bis(2-methylallyl)(1,5-ciclooctadiene) in the presence of ionic liquids containing the NTf_2 anion, at 120 bar of hydrogen and a final pressure of 180 bar (after the addition of supercritical CO_2), gamma-butyrolactone, 4-ethoxy-4-oxobutanoic acid, diethyl succinate and diethyl 2-hydroxysuccinate were mainly formed and were identified by gas chromatography coupled with mass spectrometry (GC-MS). When the ionic liquid [Bmim]NTf_2 was used it was possible to obtain the compounds gamma-butyrolactone with a selectivity of 23.4%. However, increasing the aliphatic chain of the IL cation to [C6mim] it was possible to increase selectivity of this compound up to 41.4%. Nevertheless, using a completely different IL like [Emim]OAc, the formation of such compound did not occur. The referred compound has a significant importance in biodiesel field, and it is generally used as a *building block* in the synthesis of polymers and plastics, and therefore it is a target of this project.

Changing the catalyst to palladium 5% on alumina and using ionic liquids with the [Emim] cation and different anions, new reaction conditions were studied to understand the influence of IL and catalyst in the type of products. Hence, using only 60 bar of hydrogen and around 60 bar of supercritical CO_2, compounds butane-1,4-diol, diethyl succinate and diethyl 2-hydroxysuccinate were mainly obtained. In no reaction using these new conditions was gamma-butyrolactone formed, suggesting that the ruthenium catalyst is the key factor.

Interestingly, the ionic liquid [Emim]OAc favored the formation of 1-methylpyrrolidine-2,5-dione and 1-ethylpyrrolidine-2,5-dione with high selectivity (30-60%).

The conversion of malic acid was determined through its quantification by HPLC. In two samples was possible to quantify malic acid that did not react. Hence, in these two reactions the conversion was higher than 99%. In the remaining reactions the quantification was not possible, due to the detection limit of the equipment. Therefore, a 100% conversion for these reactions was considered.

Catalysts used in these reactions were recovered by filtration, and analyzed by transmission electronic microscopy (TEM) which allowed the measurement of particles diameters. With ruthenium catalyst, nanoparticles were formed with 1.5-2.5 nm diameter.

The catalyst used in the reaction with [Bmim]NTf_2 consisted in ruthenium nanoparticles with a high level of aggregation, although the same did not happen with the catalyst used in the reaction with [Emim]OAc, where small aggregates were visible, allowing the more accurate measurements.

Ionic liquids used in the hydrogenation of malic acid were recovered by liquid-liquid extraction with an immiscible solvent. Their purity was assessed by NMR experiments, and compared with spectra from original ILs. Generally, it is possible to conclude that recovered ionic liquids were effectively recovered in high level of purity.

In summary, the goals of this project were successfully accomplished, proving the usefulness of supercritical fluids and ionic liquids in carboxylic acid hydrogenation.

Key-words: Malic Acid, Ionic Liquids, Supercritical CO_2, Hydrogenation, Green Chemistry.

Resumo

O objetivo principal deste trabalho de investigação consistiu na hidrogenação catalítica do ácido málico, utilizando líquidos iónicos como solventes e na presença de CO_2 supercrítico. Os catalisadores utilizados neste projeto foram catalisadores heterogéneos de ruténio e de paládio.

Utilizando o catalisador bis(2-metilalilo)(1,5-ciclooctadieno) de ruténio (II), na presença de líquidos iónicos com o anião NTf_2 em comum, a 120 bar de hidrogénio e uma pressão final de 180 bar (após a adição de CO_2 supercrítico), foram obtidos maioritariamente os compostos gamma-butirolactona, ácido 4-etoxi-4-oxobutanóico, succinato de dietilo e 2-hidroxi-succinato de dietilo, identificados através de cromatografia gasosa acoplada à espetrometria de massa (GC-MS). Com o líquido iónico [Bmim]NTf_2 foi possível obter o composto gamma-butirolactona com uma seletividade de 23.4%. Contudo, aumentando a cadeia alifática do catião para [C6mim] foi possível aumentar a seletividade do mesmo composto para 41.4%. Porém, utilizando um líquido iónico composto por um catião e um anião diferentes, nomeadamente o líquido iónico [Emim]OAc, não ocorreu a formação deste produto. Este composto tem uma importância significativa na área do biodiesel, sendo geralmente utilizado como *building block* na síntese de polímeros e plásticos e como tal, consiste num composto alvo deste projeto.

Mudando para um catalisador de paládio, e utilizando líquidos iónicos com o catião [Emim] em comum e diferentes aniões, foram estudadas novas condições reacionais de forma a entender a influência tanto do líquido iónico como do catalisador no tipo de compostos obtidos. Assim, diminuindo a quantidade de hidrogénio para 60 bar e usando cerca de 60 bar de CO_2 supercrítico foram obtidos maioritariamente os compostos butano-1,4-diol, succinato de dietilo e 2-hidroxisuccinato de dietilo. Em nenhuma reação utilizando este catalisador ocorreu a formação do composto gamma-butirolactona, o que sugere que a formação do composto gamma-butirolactona é favorecida pela utilização do catalisador de ruténio, e que a utilização de uma maior quantidade de hidrogénio não parecer influenciar a seletividade deste composto.

Curiosamente, em ambas as condições reacionais o líquido iónico [Emim]OAc favorece a formação dos compostos 1-metilpirrolidina-2,5-diona e 1-etilpirrolidina-2,5-diona com elevada seletividade (30-60%).

A percentagem de conversão de ácido málico foi calculada através da quantificação do mesmo por HPLC. Em duas amostras foi possível determinar a quantidade de ácido málico que não reagiu, sendo que nestas duas reações a conversão foi superior a 99%. Nas restantes reações, não foi possível quantificar o ácido málico devido ao limite de deteção do equipamento. De qualquer forma, foi considerada uma taxa de conversão de 100% para estas reações.

Os catalisadores utilizados foram recuperados após as reações através de filtração, e foram sujeitos a análise por microscopia eletrónica de transmissão (TEM) a qual permitiu medir

o diâmetro das partículas. No caso do catalisador de ruténio, formaram-se nanopartículas com um diâmetro de 1.5-2.5 nm.

O catalisador utilizado na reação com o liquido iónico [Bmim]NTf_2 mostrou ser constituído por grandes agregados de nanopartículas de ruténio, embora o mesmo não tenha ocorrido com o catalisador utilizado na reação com o liquido iónico [Emim]OAc, onde apenas pequenos agregados se formaram, tendo facilitado a observação/medição destas nanopartículas por TEM.

Os líquidos iónicos utilizados nas reações de hidrogenação do acido málico foram recuperados através de extração líquido-líquido com um solvente imiscível. A pureza destes foi avaliada através de experiências de ressonância magnética nuclear (NMR), tendo sido comparados os resultados com os espectros dos líquidos iónicos originais. De uma forma geral pode-se concluir que os líquidos iónicos foram recuperados com sucesso e com elevado grau de pureza.

Em resumo, os objetivos deste projeto foram cumpridos, comprovando a utilidade de fluídos supercríticos e dos líquidos iónicos na hidrogenação catalítica de ácidos carboxílicos.

Palavras-chave: Ácido Málico, Líquidos Iónicos, CO_2 Supercrítico, Hidrogenação, Química Verde.

List of Symbols and Abbreviations

APIs	Active pharmaceutical ingredients
BDO	Butane-1,4-diol
CCD	Charge coupled device
ChCl	Choline chloride
ρ_c	Critical density
Pc	Critical pressure
Tc	Critical temperature
DES	Deep eutectic solvents
$CDCl_3$	Deuterated chloroform
MeOD	Deuterated methanol
Et_2O	Diethyl ether
EI-MS	Electrospray ionization mass spectrometry
EDS	Energy dispersive spectroscopy
EtOAc	Ethyl acetate
GBL	Gamma-butyrolactone
GC-MS	Gas chromatography-mass spectrometry
HMBC	Heteronuclear multiple bond correlation
HPLC	High pressure liquid chromatography
HBDs	Hydrogen bond donors
3-HBL	(S)-3-hydroxybutyrolactone
IL	Ionic liquid
MeOH	Methanol
NMR	Nuclear magnetic resonance
pH_2	Pressure of H2
RTILs	Room temperature ionic liquids
$ScCO_2$	Supercritical carbon dioxide
ScE	Supercritical fluid extraction
ScF	Supercritical fluids

p	Total pressure
TCA	Tricarboxylic acid
TEM	Transmission electron microscopy
THF	Tetrahydrofuran

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1. Introduction

1.1 Motivation

During the 20th century, many of the world's canals have been suffering from pollution and forests health has started to be deteriorated by acid rains. The earth's ozone layer has been forming measurable holes, leading to the appearance of cancers and other human and environmental health outcomes. Due to this, many governments started to regulate the generation and disposals of industrial wastes and emissions.[1]

Due to this, the United States created the Environmental Protection Agency (EPA) in 1970, with the primary focus being the safety of both human and environmental health through setting and enforcing environmental regulations. The agency defined green chemistry with the "*design of products and processes which reduce or eliminate the use or formation of hazardous substances. Green chemistry applies throughout the life cycle of a chemical product from cradle to grave"*.[2]

In order to regulate and facilitate the analysis of the products life cycles a set of rules were developed. They are known as the 12 principles of green chemistry: (1) it is better to prevent waste than to treat or clean up waste after it is formed; (2) synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product; (3) wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment; (4) chemical products should be designed to preserve efficacy of function while reducing toxicity; (5) the use of auxiliary substances should be made unnecessary wherever possible and innocuous when used; (6) energy requirements should be recognized for their environmental and economic impacts and should be minimized; synthetic methods should be conducted at room temperature and atmospheric pressure; (7) a raw material or feedstock should be renewable rather than depleting whenever is technically and economically practicable; (8) unnecessary derivatization should be avoided whenever possible; (9) catalytic reagents are superior to stoichiometric reagents; (10) chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products; (11) analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances; (12) substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.[3]

As it was referred above, one of the main concerns is the possibility to optimize processes in a conscious green way. For that, the purposes are to minimize materials wastes, replace fossils-based products for new bioproducts and reduce the greenhouse gas emissions.

By definition "*biorefinery is the sustainable processing of biomass into a spectrum of marketable products and energy*". With this in mind, the efficient and sustainable use of ground-breaking and cost-effective biomass resources, for the production of bio-based products and bioenergy, should be reinforced by the use of processes of biorefinery, becoming the basis of the future bio-based economy.[4]

An example of the implementation of green alternatives, that can be used in biorefinery processes, is the use if supercritical fluids (ScF) as solvents. Their peculiar properties and different applications make them attractive for extraction and reaction methods, since they optimize the sustainability of different processes.

A supercritical fluid is a substance which temperature and pressure are above the critical values, corresponding to the inexistence of liquid and gas phase boundary and phase transition. Therefore, the properties of these fluids assume characteristics of both liquids and gases. By changing the values of pressure and temperature it is possible to improve the properties of the fluids to behave as a liquid or as a gas, depending on the conditions.

With these changes, it is also possible to change the dissolution power of the supercritical fluids, increasing the applicability of these fluids for research purposes and for industrial applications specially used for separation processes in food, pharmaceutical and cosmetic sectors.

Supercritical fluids became a better alternative as solvents, due to the ability of affecting the mass transfer induced by their viscosity and diffusion coefficient. They have values of density similar to liquids, values of viscosity comparable to gases and values of diffusion coefficients between liquids and gases.[5]

Another example of green solvents that has a great impact in green chemistry, are the ionic liquids (ILs), they are fused organic salts with melting points below 100˚C; typically their composition results of a combination of organic cations of low symmetry with a diversity of organics or inorganics anions.[6]

Ionic liquids can be used in the production of not only specific high-value products, but also compete in the more sustainable production of bulk commodities. They contribute to make the green biorefinery concept more economically sustainable and environmentally benign and more realistic, since they are no longer expensive solvents.[7]

The advantage of using ILs as green sustainable solvents, relays on the possibility of tuning the properties required, for example, the capacity to dissolve specific compounds in a selective form, depending on the right combination of cations with suitable anion. Also, the broad

temperature range in liquid state, the very small vapor pressure, no inflammability, low toxicity are properties that increase their range of applications in a green and sustainable way.[8]

1.2 Aim of the work

Initially the research project proposed for my thesis was focused on the continuation of the work previously realized by Tiago Carvalho, in Poland. The main goal was, obtain Safrole oxide through epoxidation of Safrole, and extraction of Safrole from the raw material. The reactions were supposed to be carried out using an alternative green solution, using supercritical carbon dioxide as solvent.

In Poland, all the research and theoretical part of the work was performed; however, due to the lack of conditions and materials necessary, the experimental part was not possible to be accomplished, and therefore a new research project was initiated in Portugal in July.

This project is incorporated in the project UID/QUI/50006 and its main goal is the development of a sustainable process of malic acid hydrogenation using green alternatives, such as supercritical carbon dioxide and ionic liquids as solvents.

2. Theoretical Background

2.1 Supercritical Fluids

Supercritical fluids were discovered in 1822 by Charles Cagniard de La Tour, a French engineer and physicist, in his cannon barrel experiment. He placed liquid ethanol and a ball bearing inside a sealed gun barrel and heated, observing that above a certain temperature he could no longer hear the liquid inside the tube when the barrel moved. He discovered the critical temperature is the temperature at which the substance was neither a liquid nor gas, but a single phase.[9]

The physical state of a pure substance depends on temperature and pressure conditions. The critical point is located at the upper end of the vapor pressure curve, the line of equilibrium between liquid and vapor, Figure 2.1.

At the critical point, defined by a critical temperature (Tc) and a critical pressure (Pc), the boundary of the liquid and the gas phases disappears.[5]

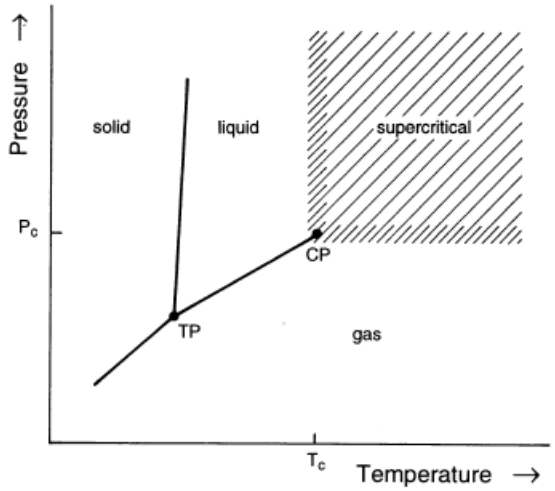

Figure 2.1 - Phase diagram of a pure substance.[10]

A pure substance is considered to be in supercritical state if its temperature and pressure are above the critical values. [10]

The ScF have unique chemical and physical properties that affect directly the mass transfer, the viscosity and the diffusion coefficient, Table 2.1.

Table 2.1- Properties of ScF, liquids and gases.[5]

	Liquid	**ScF**	**Gas**
Density (kg/m^3)	600-1600	200-900	0.6-2
Viscosity (Pa.s)×10^5	20-300	1-9	1-3
Diffusion Coefficient (m^2/s)×10^9	0.2-2	20-70	10000-40000

In these supercritical conditions, fluids are in fact high pressure gases, but present properties that can be varied continuously between those characteristic of either a liquid or a gas, just by changing pressure and/or temperature. The fluid may be made more similar to a gas, being highly compressible, diffusing through solids and having low values of viscosity. On the other hand, it may be similar to a liquid, due to its comparable density and solvating power by being able to dissolve materials like a liquid but with mass transfer much favorable. These properties may bring advantages to the use of these fluids as solvents.[11],[5]

The ability of ScFs to change their dissolution power in a continuous way, by only adjusting the values of pressure and temperature, makes them very attractive to research as well as to industrial purposes. Small changes in the values of pressure and temperature, close to the critical point, can modify the properties of the fluids to resemble more to a liquid or more to a gas, depending on the necessary conditions. These values of pressure and temperature will be different depending on the compound used, Table 2.2.

Table 2.2- Most common supercritical solvents.[5]

Supercritical Solvent	**Tc (K)**	**Pc (MPa)**	**ρc (mol/L)**
Carbon Dioxide	304.18	7.380	10.6
Water	647 +/- 2	22.064	17.9
Ethylene	282.5 +/- 0.5	5.06 +/- 0.05	7.63 +/- 0.004
Ethane	305.3 +/- 0.3	4.9 +/- 0.1	6.9 +/- 0.4
Propane	369.9 +/- 0.2	4.25 +/- 0.01	5.1 +/- 0.4

Supercritical fluids may replace organic solvents, in certain favorable conditions.

Supercritical fluid extraction (ScE) has found useful applications in the processing of materials, such as coffee, tea, tobacco, hops and spices, in the food, pharmaceutical and cosmetic sectors to accomplish the separation of interesting components.[5]

2.2 Supercritical Carbon Dioxide

Supercritical carbon dioxide ($ScCO_2$) is the most common supercritical fluid used, due to is low critical temperature (Tc=304 K), just above ambient temperature, and its reasonable critical pressure (pc= 7.98 MPa). The transport properties of $ScCO_2$ are very attractive, since it has low viscosity and high diffusion coefficients.

Carbon dioxide as supercritical fluid is a clean solvent and very interesting to researcher's due to is versatility and, because of its non-toxic, and non-flammable properties; it is chemically inert and it is available on the market at low prices. Another advantage is the possibility of being removed from a system by a simple depressurization step and because it is possible to be recovered during the process, not creating a problem related to the greenhouse effect.[5]

The use of $ScCO_2$ in the synthesis and processing of polymers because of its physical properties that allow processing at low temperatures. The solubility of supercritical CO_2 in many polymers is extensive and depends on temperature and pressure, as well as on weak interactions with the functional groups in the polymer. Dissolved CO_2 alters the physical properties of polymers like density, diffusivity and swollen volume, making a great potential as plasticizer in polymer processing, which is normally done at high temperatures.

It can also be used in the processing of different biodegradable/biocompatible polymers for applications in the pharmaceutical and medical fields, whereas its importance relays on the low thermal stability of biodegradable polymers and the lack of organic solvents in their process.[12]

2.3 Ionic Liquids

Ionic liquids are organic salts which composition usually results of a combination of organic cations of low symmetry and with a diversity of organics or inorganics anions. The choice of the anion, normally, controls the chemical properties and the functionality of the IL; moreover, the stability of the IL, is often defined by the cation used. Theoretically, there are countless combinations possible, but only around 1000 are described in literature.[6]

Conventional organic solvents, such as hexane, methanol, acetone and others, are highly used in synthetic processes. In the past few years, researchers have been trying to find new environmental friendly and sustainable alternatives for these toxic and hazardous solvents.

Recently, ionic liquids (ILs) have gained more attention from scientists, as they have interesting properties such as low melting points (below 100 ºC), negligible vapor pressure, high thermos stability, high ionic conductivity, large electrochemical window, ability to solvate compounds of widely varying polarity, ability to dissolve a wide range of inorganic and organic materials, immiscibility with organic solvents that makes them a good non-aqueous alternative in biphasic systems.[13]

Another important feature of ILs is that they have high decomposition temperatures (normally above 200-300 ºC), and also it is possible to prepare ionic liquids that are liquid at room temperature, the well-known room temperature ionic liquids (RTILs). But the main characteristic of ionic liquids for green chemistry applications is their extremely low vapor pressure. This absence of volatility which prevent ILs from escaping to the atmosphere, contrarily to low-boiling organic solvents, is their main credential as sustainable solvents.[14],[15]

Ionic liquids have been termed “designer solvent” because many ionic liquids have been developed for a specific chemical reaction or process (e.g. extraction); both cation and anion can be independently modified and designed to enable the production of new useful materials, maintaining the main properties of an IL.

This makes ILs very attractive as reaction media in the preparation of new materials for the pharmaceutical and chemical industries.[16],[17]

Nowadays, pharmaceutical industries are facing several challenges mostly related to business models, but there is also a need for new scientific advances for the preparation of effective drugs and development of new therapies.

Ionic liquids can be used either to prepare Active Pharmaceutical Ingredients (APIs) or as media for their preparation. The importance of ILs in the preparation of APIs is related to the possibility of enhancing the properties needed, such as increasing the solubility in water and permeability, increasing the bioavailability and drug delivery and in the elimination of polymorphism. On the other hand, reactions carried out in ILs are often faster and easier, than using conventional organic solvents, due to the fact that no special apparatus is required; however, thermodynamics and kinetics are completely different using conventional organic solvents or using ILs and there is no universal catalytic system for all syntheses and every reaction may require a specific ionic liquid.[18],[19]

As mentioned above, ILs also have a high utility in chemical industries as they can be used, for instance, to prepare new biodiesel derivatives. Once again, they can be used either as catalyst, with technical, economical and environmental benefits as they are less corrosive, ease of manipulation, recyclable, applicable for continuous processes and producing less water waste; or as media for biodiesel production.[20]

An ionic liquid based catalyst is able to reduce the number of reaction and purification steps required for biodiesel preparation. These types of ionic liquids are also associated with

catalyst recycling where it is possible to achieve 100% of reaction conversion with 100% selectivity by avoiding thermodynamic limitations and competition from parallel reactions.[21]

Deep eutectic solvents (DES)[1] considered the new generation of ILs, share a number of attractive solvent feature with regular ILs, although research community is ambivalent whether to call them ILs or not.[22]

These DESs are believed to be more environmentally benign when compared to traditional ILs, because they can be prepared from readily accessible chemicals and they have low toxicity since they derive from choline chloride (ChCl), renewable chemicals, and are biodegradable. Choline chloride is an organic salt commonly used for DESs, due to its biocompatibility and most of the hydrogen bond donors (HBDs) are cheap and environmentally benign such as urea, glycerol or carboxylic acids. Some authors suggested the combination of DESs and ILs, and for example, the eutectic mixture of choline chloride and zinc chloride was used as Lewis acid catalyst for the transesterification of soybean oil in methanol, with 55% conversion under optimized conditions.[23]

Ionic liquids are also reported in literature as excellent extraction solvents in biodiesel production for different purposes namely in lipid extraction from biomass, in the extraction of free fatty acids prior the reaction, in the extraction of glycerol from biodiesel after the reaction and in the extraction of unsaturated fatty acid esters from biodiesel.[22]

2.4 Hydrogenation in Supercritical CO_2

Catalytic hydrogenation consists of a chemical reaction occurring between molecular hydrogen and an element or compound, usually in the presence of a catalyst.[24]

It is a very useful chemical reaction for organic chemists as it promotes the transformation of a wide range of compounds into others. Some examples are the hydrogenation of alkynes and alkenes into alkanes; hydrogenation of aldehydes, ketones, carboxylic acids, esters obtaining the corresponding alcohols; and the hydrogenation of amino groups resulting in amines.

Usually, this type of reactions is accomplished in the presence of a catalyst, either homogeneous or heterogeneous.

Heterogeneous catalytic hydrogenation reactions may be notoriously slow, especially when multiple phases (gas, liquid, solid) are involved. Common liquid solvents, exhibit low solubility of molecular hydrogen. By replacing the traditional organic solvents with supercritical

[1] Deep eutectic solvents incorporate one or more compound in a mixture form, to give a eutectic with a melting point much lower than either of the individual components. They are commonly based on mixtures of quaternary ammonium salts with hydrogen bond donors.

CO_2 results improve substantially. This way, CO_2 acts as a solvent, in which many reactants are soluble, including H_2 resulting in higher solubility of H_2 in the reactants. The recovery of the final product is generally easy, and since the pressure is removed by depressurization, the product can be recovered without solvents. This technology is considered a green methodology by eliminating the environmental problems associated to conventional solvents.[25]

Another advantage of using supercritical CO_2 is that for some reactions, there is a possibility to increase the yield rate or to improve the selectivity. This is due to the fact that $ScCO_2$ is miscible in gases as H_2, enhancing the reactions rate.[26]

Moreover, a unique feature of using supercritical fluids as solvents is the possibility to. through small changes in pressure and/or temperature, enhance the properties desired, such as density, polarity, viscosity, diffusivity and solvent strength.[27]

2.5 Hydrogenation with Ionic Liquids

As has been mention before, one of the most appealing conditions of ILs is the possibility of customized them and their physico-chemical properties, making possible for ILs to provide means of catalyst immobilization.

The selectivity and product distributions of an hydrogenation reaction can be improved by the nature of the anion of the ionic liquid; however it is possible to enhance others desired reaction parameters by adjusting the cation or the anion, whence the advantage of using ILs in hydrogenation.[28]

Ionic liquids have an important influence in the selectivity of a chemical reaction, for example, ILs can modify the selectivity pattern of a heterogeneous solid catalyst in hydrogenations, as it I showed by the catalytic heterogenous hydrogenation of limonene in $ScCO_2$ using different ionic liquids.[29]

As described before, the use of a solid catalyst with an ionic liquid layer, is another example of ionic liquids' influence in the selectivity of heterogenous hydrogenation reactions. This concept relies on coating the internal surface of the catalyst with an ionic liquid, improving the selectivity.[30]

The possibility of recycling the catalyst is one of the advantages of the use of ILs, since it can improve the performance of the catalyst. This is due to the inert reaction medium that ILs provides due to their non-nucleophilic and weakly co-ordination of many ILs.[31]

2.6 Malic Acid

Malic acid is a naturally existing four-carbon dicarboxylic acid and an intermediate in the citric acid cycle, also known as tricarboxylic acid cycle (TCA cycle). Malic acid has two stereoisomers, a left-handed L-form and a right-handed D-form. Only L-malic acid occurs naturally in biological systems. It is present in all fruits and many vegetables and it is generated in fruit metabolism. Malic acid fermentation leads to the formation of lactic acid, which is involved in many biological processes in human body and can be used in pharmaceutical, cosmetic industry and as flavor enhancer in food industry.[32]

Malic acid and succinic acid belong to the group of C4 dicarboxylic acids. This class of acids can be converted into butane-1,4-diol (BDO) that can be further converted into numerous chemicals, including plastics, polymers and resins.

The high-pressure catalytic hydrogenation of L-malic acid using a ruthenium-base catalyst in a fixed-bed reactor has been developed for the preparation of (S)-3-hydroxybutyrolactone (3-HBL). However, this process employs hazardous processing conditions and expensive catalyst and purification processes. The compound 3-HBL is widely used in the pharmaceutical industry as a building block for the preparation of cholesterol-reducing drugs.[33]

The hydrogenation of the methyl ester of malic acid to gamma-butyrolactone (GBL), butane-1,4-diol (BDO) and tetrahydrofuran (THF) using Cu/ZnO-based catalyst, are other example of the application of this dicarboxylic acid. Hence, using biomass-based malic acid it is possible to obtain these compounds avoiding the use of petroleum feedstocks.[34]

According to literature, malic acid was considered one of the top 12 potential biomass-derivable “building block” for chemical synthesis. These sugar-derived products can be converted in fuels and high value chemicals and materials, which means that the biomass-derived products can became an economical driver for biorefinery, improving the efficiency, productivity and cost-effectiveness of all energy related products.[35]

In Table 2.3 are presented some chemical properties of malic acid.

Table 2.3- Properties of malic acid.[36]

Chemical Formula	$C_4H_6O_5$
Molar Mass	134.09 g/mol
Density	1.609 g/cm3
Melting Point	403 K
Solubility in Water	558 g/L at 293 K

The hydrogenation of malic acid has not been significantly studied, but Bair S. Bal'zhinimaev *et al*, reported the production of (s)-3-hydroxy-ɣ-butyrolactone and (S)-1,2,4-butanetriol. This hydrogenation products are valuable chiral building blocks for the production drugs like Crestor, which is used to lower cholesterol.

In this article, the work was concentrated in a selective hydrogenation of an aqueous solution of L-malic acid to lactones and alcohols, using a catalyst preparation by the sequence introduction of rhenium and palladium precursors, with activated carbon as catalyst support. For the reaction, the hydrogen pressure was 90 bar, with a flow rate of 1 L/h and the reaction temperatures were of 90, 100, 110, 130 and 130 C under stirring at 700 rpm.[37]

When compared both hydrogenation reactions of L-malic acid, in the reactions studied in this work was possible to use lower pressures of hydrogen and ionic liquids were used not only as solvents but also as catalysts support. Over all, in this project there is the preoccupation of using green alternatives and safer reaction conditions, making this project more sustainable and more conscious to the environmental concerns of nowadays.

3. Materials and Methods

3.1 Chemicals

The heterogenous catalysts used in this work were Palladium, (5 wt%) on alumina in powder, and Ruthenium (II), bis(2-methlylally)(1,5-cyclo-octadiene) (CAS Number 12289-94-0), were obtained from Sigma-Aldrich.

The ionic liquids, 1-ethyl-3-methylimidazolium chloride, (Emim)[Cl], (purity >98%, CAS Number 65039-09-0); 1-ethyl-3-methylimidazolium tosylate, (Emim)[OTs], (purity 99%, CAS Number 328090-25-1); 1-ethyl-3-methylimidazolium diethyl phosphate, (Emim)[diethy-phosphate], (purity >98%, CAS Number 848641-69-0); 1-ethyl-3-methylimidazolium dicyanamide, (Emim)[DCA], (purity >98%, CAS Number 370865-89-7) and 1-ethyl-3-methylimidazolium acetate, (Emim)[OAc], (purity >95%, CAS Number 143314-17-4), were acquired from IoLiTec (ionic liquids Technologies).

The ILs 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide, (Bmim)[NTf_2], (purity >98%, CAS Number 174899-83-3); 1-decyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide, (C6mim)[NTf_2], (purity >98%, CAS Number 382150-50-7) and 1-butyl-3-methylimidazolium dicyanamide, (Bmim)[DCA], (purity >98%, CAS Number 448245-52-1), were supplied from SOLCHEMAR.

Finally, the ionic liquid 1-ethyl-3-methylimidazolium 2-(2-methoxyethoxy)ethylsulfate (Emim)[methoxy ethoxy ethyl sulfate] (purity >=98%, CAS Number 790663-77-3), was bought from Merck.

L-(-)-Malic acid (purity 99%, crystalline powder, CAS Number 97-67-6), was obtained from Alfa Aesar.

Chloroform, ($CHCl_3$), (purity >=99%, CAS Number 67-66-3) and ethyl acetate, (EtOAc), (purity >=99.9%, CAS Number 141-78-6), were obtained from Carlo Erba reagents. Methanol, (MeOH), (purity >=99.9%, CAS Number 67-56-1) and diethyl ether, (Et_2O), (purity >=99.7%, CAS Number 60-29-7) were bought in Sigma Aldrich Chemicals. The Acetone (purity >=99.8, CAS Number 67-64-1) was supplied from Honeywell Riedel-de Haën. Deuterated chloroform, ($CDCl_3$), (purity D, 99.8%, with silver foil, CAS Number 865-49-6) and deuterated methanol, (MeOH-D4), (purity d, 99.8%, CAS number 811-98-3) were from Cambridge Isotope Laboratories.

Hydrogen and carbon dioxide bottles were bought from Air Liquid, with purity of 99.98 mol% and were used without any other purification.

3.2 Experimental Procedure

3.2.1 Reaction Procedure

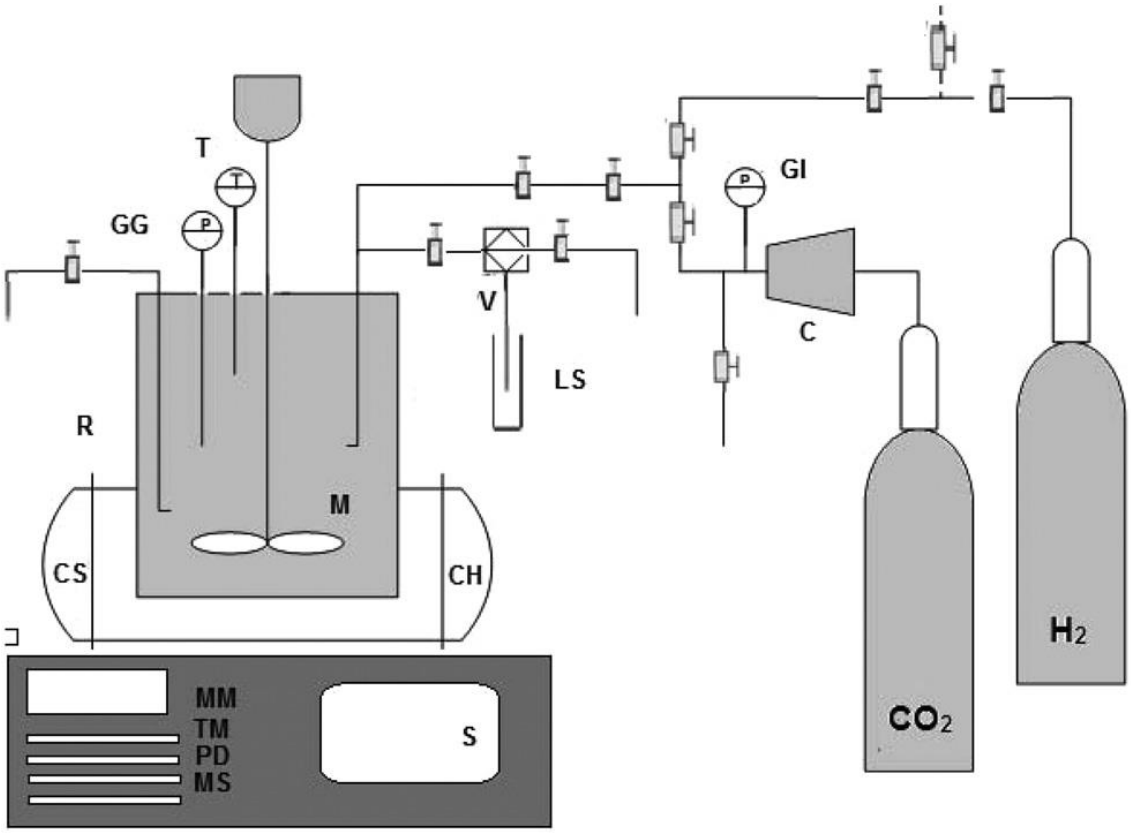

Figure 3.1- Scheme of reaction apparatus: R- bench top reactor with a removable heat vessel equipped with M- magnetic drive, SR- safety rupture disc, GI- gas inlet valve, GG- pressure gauge, GR- gas release valve, LS- liquid sampling valve, T- thermocouple, CH- ceramic fiber heater, CS- cooling system; C- compressor pump, V- HPLC valve with a sampling loop of 100 µL; reactor controller equipped with S- heater switch, M- motor control modules, TM- tachometer (temperature) display module, PD- pressure display module, and MS- motor speed control module. [38]

The reactions were performed in a high-pressure system with a PARR bench top reactor which schematic diagram is shown in Figure 3.1. It is composed mainly of a 25 mL Parr Company stainless steel reactor - Series 4591 micro reactor systems, with a removable heat vessel equipped with a magnetic drive, safety rupture disc, gas inlet valve, pressure gauge, gas release valve, liquid sampling valve and a thermocouple placed in a ceramic fiber heater with cooling capability. [38]

L-malic acid (5.59 mmol, 0.75 g), selected ionic liquid (2 mL) and bis(2-methlylally)(1,5-cyclo-octadiene)ruthenium(II) (5.5% mol, 0.1 g) or palladium 5% (w/w on alumina) (5.5% mmol 0.666 g) were introduced in the reactor. The reactor was closed, sealed and deoxygenated under vacuum prior to the slowly addition of 120 bar or 60 bar of H_2 in the system. The reactor temperature was increased to 393.15 K, allowing the system to stabilize afterwards due to the

increase on pressure with the increase of temperature. Then, CO_2 was introduced until the system reached 180 bar or 120 bar of total pressure and the reaction started once stirring was initiated. Reaction was carried out for 6h or 20h, using Ru-based or Pd-based catalyst, respectively.

When the reaction finished, the reactor was slowly cooled up to room temperature and the system was slowly depressurized until atmospheric pressure. The reaction mixture was dissolved in acetone and methanol and recovered from the vessel. Catalyst was filtered off under vacuum, washed with acetone and methanol and allowed to dry overnight. The reaction mixture was concentrated in rotavapor under vacuum. A known volume of diethyl ether was added to the concentrated mixture, and ionic liquid was recovered by liquid-liquid extraction; the extraction step was repeated thrice. The diethyl ether layers were combined and solvent was allowed to evaporate in the hood at atmospheric pressure.

A sample of the reaction mixture was analyzed by GC-MS and HPLC to identify the products and to calculate the percentage of malic acid conversion, respectively.

3.2.2 TEM

Analysis of catalysts by transmission electron microscopy (TEM) was performed in the laboratory of Electron Microscopy of Instituto Superior Técnico. The experiments were performed in the model Hitachi H-8100 TEM, where the samples were placed in a copper support, with a ThermoNoran light elements EDS detector and CCD camera for image acquisition.

3.2.3 NMR

Nuclear magnetic resonance (NMR) was used to confirm the purity and possible reusability of all ionic liquids after the extraction process. ^{1}H-NMR and ^{13}C-NMR experiments were performed in a 400MHz Bruker equipment.

Deuterated chloroform was used as solvent in most of the experiments and data analysis was performed based on its chemical shift. Deuterated methanol was used whenever the IL/reaction mixture was not soluble in $CDCl_3$. Chemical shifts are given in ppm.

3.2.4 GC-MS

GC-MS analyses of reaction mixtures were performed using a gas chromatograph model GC Agilent 6890N coupled with an electrospray ionization mass spectrometry (EI-MS) model Thermo DSQ. Chromatographic separation was achieved on a VF5-ms column (30 m × 0.25 nm ID × 0.25 mm film thickness) using helium as the carrier gas at 1.0 mL/min in a constant flow rate mode. The injector temperature was 250 °C. The oven temperature was at 40 °C, increased by

10 °C/min to 300 °C and held at this temperature for 10 min. The temperature for EI-MS was 200 °C with time of “solvent delay” of 3 min.

3.2.5 HPLC

To detect the malic acid conversion, high performance liquid chromatography (HPLC) analyses were performed on Waters 600 chromatography equipped with a Biorad Aminex HPX 87H (300 × 7.8 mm) column and a UV/Vis detector (wavelength set to 210 nm). the oven temperature was set to 30 °C. Samples were prepared in 10% MeOH and diluted in water ultrapure with final matrix of 10% of MeOH. Separation was achieved using 10 mN H_2SO_4 as the mobile phase with a flow rate of 0.6 mL/min and injection volume of 20 μL.

4. Results and Discussion

As mentioned before, the main goal of this work was to understand the importance of $ScCO_2$ and ionic liquids as green solvents in the hydrogenation of malic acid.

The hydrogenation of malic acid was performed in two series of reactions, both accomplished in a supercritical CO_2 system but using different conditions, different catalysts and different ionic liquids, represented in Table 4.1 and Table 4.2.

The structure of the starting material, L-malic acid, is presented in Figure 4.1.

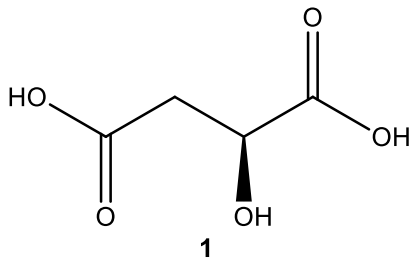

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Figure 4.1- Structure of the L-malic acid (1).

In Figure 4.2 are represented the structures of the ionic liquids used in the reactions of this research project.

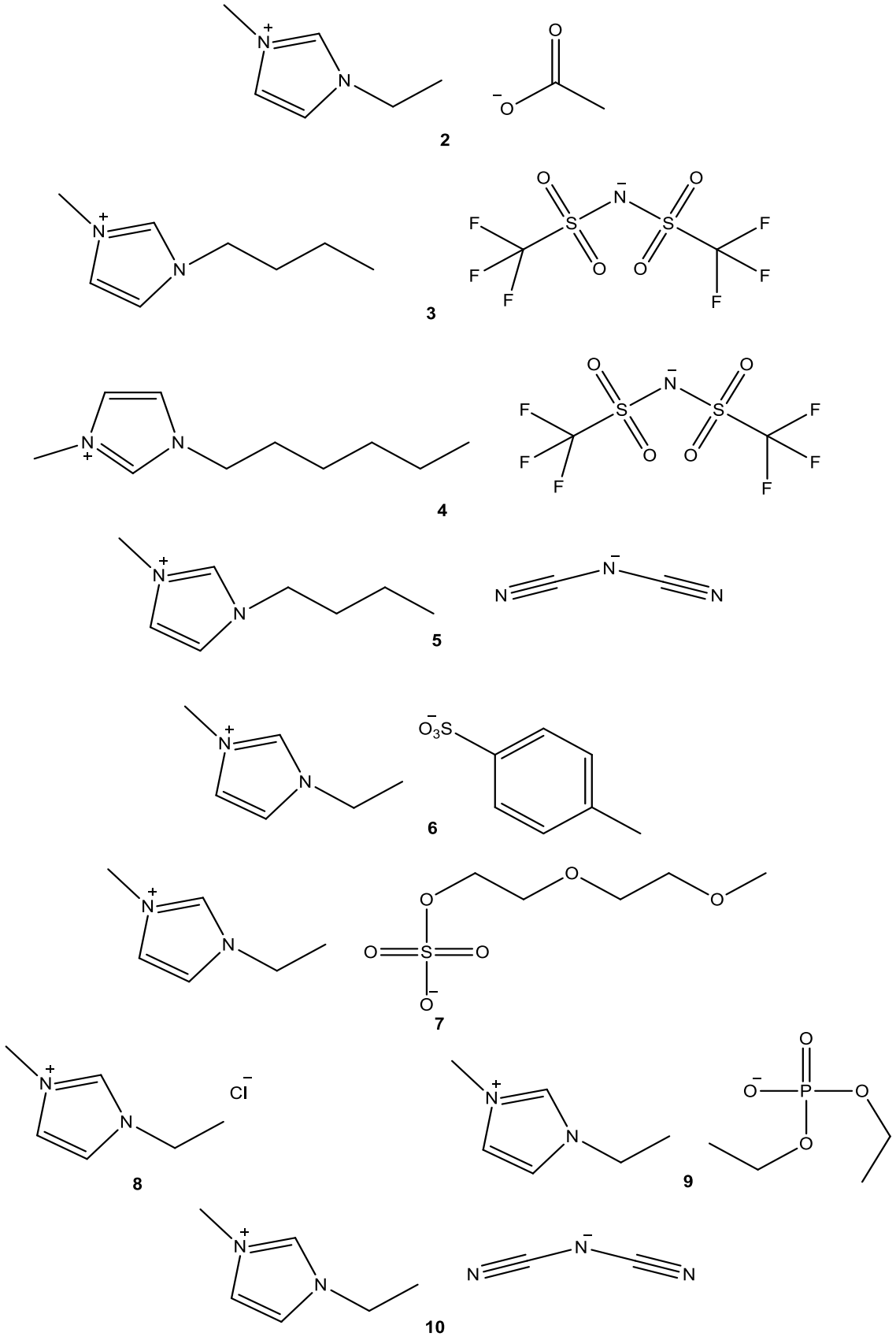

Figure 4.2- Ionic Liquids used in the reactions: [Emim]OAc (2), [Bmim]NTf_2 (3), [C6mim]NTf_2 (4), [Bmim]DCA (5), [Emim]OTs (6), [Emim]methoxy ethoxy ethyl sulfate (7), [Emim]Cl (8), [Emim]diethyl-phosphate (9) and [Emim]DCA (10).

The compounds identified by GC-MS are represented in Figure 4.3.

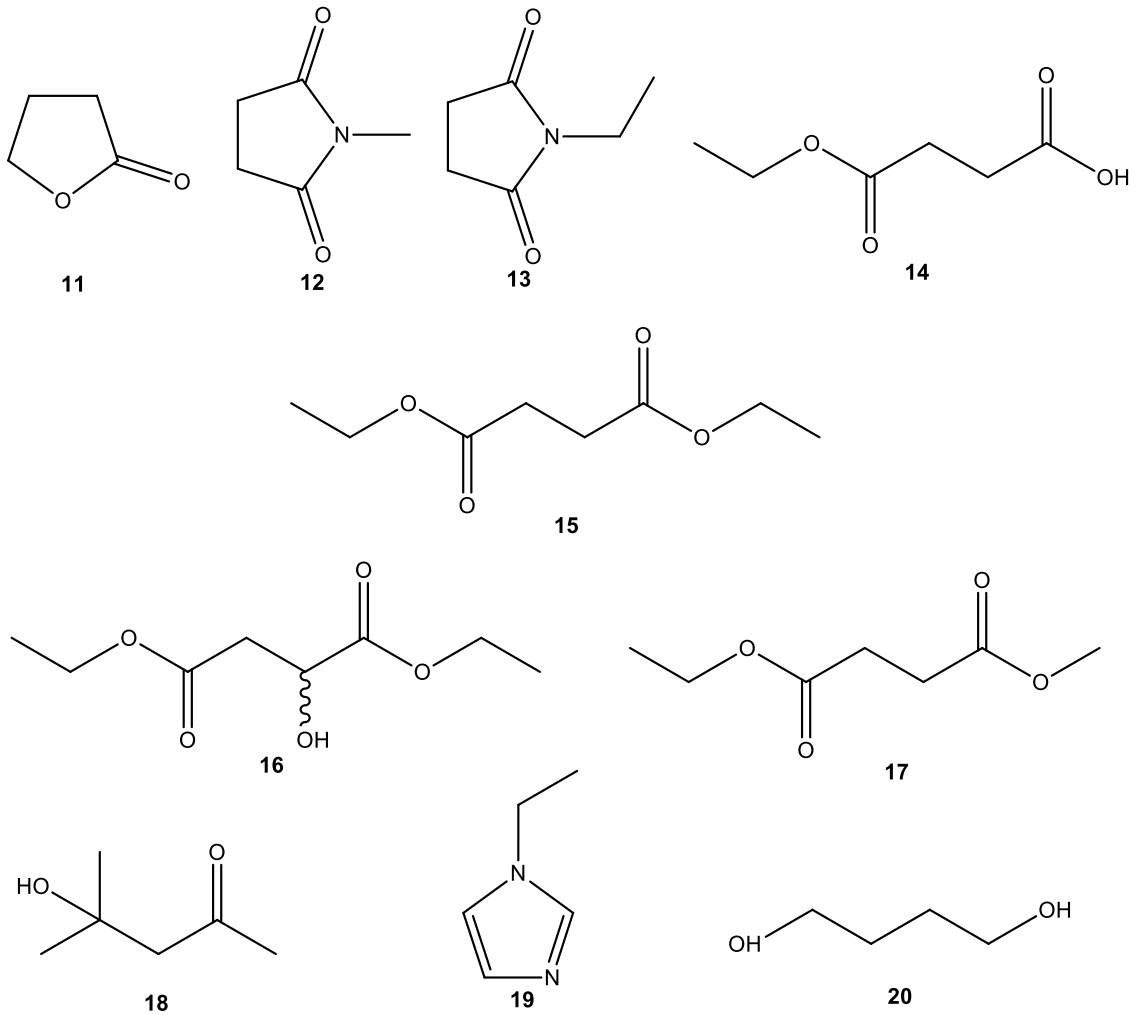

Figure 4.3- Possible products obtained in the reactions: γ-butyrolactone (11), 1-methylpyrrolidine-2,5-dione (12), 1-ethylpyrrolidine-2,5-dione (13), 4-ethoxy-4-oxobutanoic acid (14), diethyl succinate (15), diethyl-2-hydroxysuccinate (16), ethyl methyl succinate (17), 4-hydroxy-4-methylpentan-2-one (18), 1-ethyl-1H-imidazole (19) and butane-1,4-diol (20).

4.1 Selectivity

The selectivity[2] of the reaction towards each compound was calculated based on the analysis of the chromatogram obtained by GC-MS. This ratio was calculated dividing the area of each peak, by the total area of all peaks presented in the chromatogram.

[2] Amount of desired product that was formed in ratio to the undesired product(s).

In the first group of reactions, 120 bar of H_2, 393.15 K, final pressure of 180 bar for 6 h were the conditions used. The ruthenium based catalyst was (bis(2-methlylally)(1,5-cyclo-octadiene)ruthenium(II)) and the ionic liquids were [Emim]OAc, [Bmim]NTf_2 and [C_6mim]NTf_2.

Table 4.1- Selectivity of products obtained in the hydrogenation of malic acid in ScCO2 using Ru-based catalyst.

Entry	Ionic Liquid	Selectivity (%)					
		11	**12**	**13**	**14**	**15**	**16**
1	[Emim]OAc	-	31.0	69.0	-	-	-
2	[Bmim]NTf_2	23.4	-	-	36.9	27.9	11.8
3	[C_6mim]NTf_2	41.4	-	-	27.7	30.9	-

According to Table 4.1, entries 2 and 3, it is possible to observe that using the same anion but changing the cation in IL, the products obtained are the same and with slightly similar selectivities. This may suggest that the cation does not have a high influence in the products that are formed.

Using an entirely different ionic liquid (entry 1), which contains an emim cation and an acetate anion, the products obtained are completely different, suggesting that the ionic liquid influences the type of products formed in this type of reactions.

Gamma-butyrolactone (11), has important paper in the fine chemical and pharmaceutical industries, since it is used as a solvent and also as a starting material for the production of C4 chemicals, was formed only when the liquids [Bmim]NTf_2 and [C_6mim]NTf_2 were used. Compounds 4-ethoxy-4-oxobutanoic acid (14) and diethyl succinate (15) also were obtained solely whenever these ILs were used. Since the anion is the same in these ILs, this may suggest that the formation of these compounds can be associated to the NTf_2 anion. Further experiments to confirm this possibility are required, using for example the same ionic liquid but in different conditions of pressure or even the use of ionic liquids with the same cation but with different anion at the same pressure conditions.[39]

These results also suggested that increasing the chain length on the cation moiety, it is possible to increase the formation of compound 11. However, further studies are also required to confirm this.

In the second set of reactions, the conditions used changed to 60 bar of H_2, 393.15 K, final pressure of 120 bar for 20 h. The catalyst used was Pd (5% on alumina, powder) and the

ionic liquids used were [Emim]OAc, [Bmim]DCA, [Emim]OTs, [Emim]methoxy ethoxy ethyl sulfate, [Emim]Cl, [Emim] diethylphosphate and [Emim]DCA.

*Table 4.2- Selectivity of products obtained in the hydrogenation of malic acid in ScCO2 using Pd catalyst. *This reaction was performed with pH_2=120 bar, total pressure p=180 bar and reaction time of 6 h.*

Entry	Ionic Liquid	Selectivity (%)								
		12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
1	[Bmim]DCA	-	-	-	-	-	-	15.2	-	-
2*	[Emim]OAc	30.2	65.2	-	-	-	-	-	2.8	-
3	[Emim]OAc	29.0	63.0	-	-	-	-	-	7.9	-
4	[Emim]OTs	-	-	32.9	54.1	13.0	-	-	-	-
5	[Emim]methoxy ethoxy ethyl sulfate	-	-	2.3	20.4	1.7	0.9	-	-	66.8
6	[Emim]Cl	1.8	-	49.3	17.1	1.0	7.6	-	-	23.2
7	[Emim]diethyl-phosphate	11.9	20.7	27.5	34.3	-	1.4	4.2	-	-
8	[Emim]DCA									

In these new conditions, the same analogy was followed; using ionic liquid with the same cation but different anion moieties.

According to Table 4.2, it is possible to observe that there are more compounds formed in comparison with the first set of reactions.

Again, with IL [Emim]OAc (entries 2 and 3), results are completely different from the rest of ILs with formation of different scaffolds, even using the same conditions as in Table 4.1.

Changing the anion but maintaining the cation, resulted in the formation of different compounds, and it was possible to observe that even when the same products are formed, their selectivies are significantly different.

Another interesting fact is that gamma-butyrolactone was not formed when [Emim]OAc was used, even using the harsh conditions from Table 4.1 (entry 2, Table 4.2)

In the Table 4.3, is presented a comparison between the reactions of malic acid hydrogenation with the ionic liquid [Emim]OAc, carried at 393.15 K in different reaction conditions.

Table 4.3- Comparison of the reaction of hydrogenation of Malic Acid in the $ScCO_2$ and IL system, with the same IL but with different conditions.

Entry	Liquid Ionic	Reaction Time (h)	Catalyst	pH_2 (bar)	Total pressure, p (bar)	Selectivity (%)		
						12	13	19
1	[Emim]OAc	6	Ru-based	120	180	31.0	69.0	-
2	[Emim]OAc	6	Pd	120	180	30.2	65.2	2.8
3	[Emim]OAc	20	Pd	60	120	29.0	63.0	7.9

It was possible to observe that in opposite to what happens with Ru-based catalyst (entry 1), palladium (entry 2 and 3) promoted the formation of compound 19. In the same reaction conditions but changing the catalyst, the proportion between compounds 12 and 13 is more or less maintained (entries 1 and 2).

Comparing results from entries 2 and 3, it was possible to conclude that results do not change significantly when harsher conditions are used.

In conclusion, the results suggested that the catalyst and ionic liquid may have more influence in the type of products formed rather than the amount/pressure of hydrogen used. Hence, depending on what compounds are desired the catalyst/IL must be chosen accordingly.

Moreover, it is possible to conclude that the products obtained in the hydrogenation of malic acid are very similar to those obtained from succinic acid, especially the compounds ɣ-butyrolactone (11), butane-1,4-diol (20) and pyrrolidines (12 and 13) that are products from both hydrogenation reactions.[40]

Comparing the results obtained herein and in previous work, focused on hydrogenation of succinic acid, the products 1-methylpyrrolidine-2,5-dione (12), 1-ethylpyrrolidine-2,5-dione (13), diethyl succinate (15) and ethyl methyl succinate (17) are products in both projects, although different conditions of pressure, temperature and catalysts were used.[38]

Anion choice is a critical parameter while selecting the ionic liquid for hydrogenation reactions, but solvent polarity also plays an important role since it facilitates the adsorption of non-polar substrates on the catalyst, while non-polar solvents provide the opposite effect.[31]

Comparing the results from both projects, it was possible to observe that, in fact the ionic liquid had high influence in the products obtained. For example, the formation of 1-methylpyrrolidine-2,5-dione (12), 1-ethylpyrrolidine-2,5-dione (13), only occured when the ionic liquid contained an emim cation; diethyl succinate (15) and ethyl methyl succinate (17) were never

obtained when [Emim]OAc was used as solvent, however using a different anion such as OTs or Cl, they were formed in the same conditions.

4.2 NMR Analysis

One of the goals of this work was to extract the ionic liquids from each reaction, purify them by the removal of all compounds resulting from the hydrogenation reaction; and test them as reusable solvents, one of the twelve principles of green chemistry.[3]

As described before in “Materials and Methods” section, a liquid-liquid extraction was carried out to purify the IL; afterwards NMR was used to confirm their purity by comparison with non-used ionic liquids data.

The chemicals shifts in a NMR spectrum depend on the solvent used; therefore, deuterated chloroform ($CDCl_3$) was the chosen solvent because most of ionic liquids are completely soluble in it. Although some are only partly soluble in $CDCl_3$, it was possible to obtain accurate data in this solvent. The only spectrum where it was used another solvent was for the spectrum of [Emim]Cl, in which MeOD was used.

Spectral data from all ionic liquids recovered from the reactions are presented in the Appendix section, including the ^{1}H-NMR and ^{13}C-NMR data of the ionic liquid after reaction, and the superimposed spectrum of original IL with the IL after reactions.

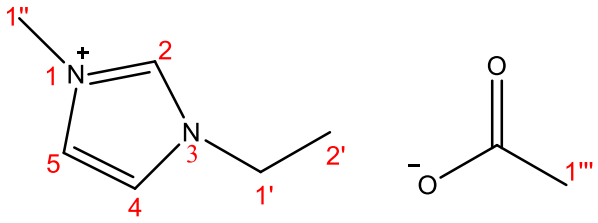

Figure 4.4- Atom numbering of [Emim]OAc for NMR analysis.

According to the structure of [Emim]OAc, Figure 4.4, it is possible to calculate the total number of protons as 14, which means that integration of all signals from the ^{1}H-NMR should be 14 in the proton spectrum.

The solvent signal ($CDCl_3$) appears at δ 7.26 ppm.[41]

The first signal identified was the signal at δ 1.42 ppm which corresponds to H-2’, it consists in a triplet due to its coupling with H-1’, and integrates 3 protons with a coupling constant of J=7.3 Hz. The signal of H-1’ at δ 4.19 ppm, appears as a quartet due to the coupling with 3 protons, from H-2’, with J=6.8 Hz and J=14,2 Hz.

In the spectrum there are 2 signals, at δ 1.86 ppm and at δ 3.89, both integrating 3 protons that correspond to H-1'' and to H-1'''. Analyzing the structure, it is possible to assign the first signal to H-1''' and the later to H-1'' because the protons from the acetate anion appear in a higher field than the proton of a methyl group bonded to a nitrogen atom.

Regarding the imidazolium protons, the signal of H-4 and H-5 should be presented as doublets. In the spectrum, it is shown a signal similar to a doublet integrating 2 protons at δ 7.34 ppm corresponding to H-4 and H-5. These two signals overlap because they are chemically similar.

In summary, all the signals were identified and assigned, confirming the structure of [Emim]OAc. Since no other significant signals appear in the baseline resulted from an impurity, it is possible to conclude that the recovery of the IL after the reaction was successfully accomplished and IL might be reused in future reactions.

[**Emim]OAc (2): ^{1}H-NMR ($CDCl_3$), δ (ppm)** 1.42 (t,3H, J=7.3 Hz, H-2'); 1.86 (s, 4H, H-2 H-1'''); 3.86 (s, 3H, H-1''); 4.19 (q, 2H, J=6.8 Hz J=14.2 Hz, H-1'); 7.34 (s, 2H, H-4 H-5). **^{13}C-NMR ($CDCl_3$), δ (ppm)** 15.3; 22.7; 32.1; 36.1; 44.9; 121.6; 123.5; 137.3; 176.0.

As an example, the ^{1}H-NMR spectrum of the IL [Bmim]NTf_2 used in one of the hydrogenation reactions and the non-used IL were superimposed and the resulted spectrum is represented in Figure 4.5.

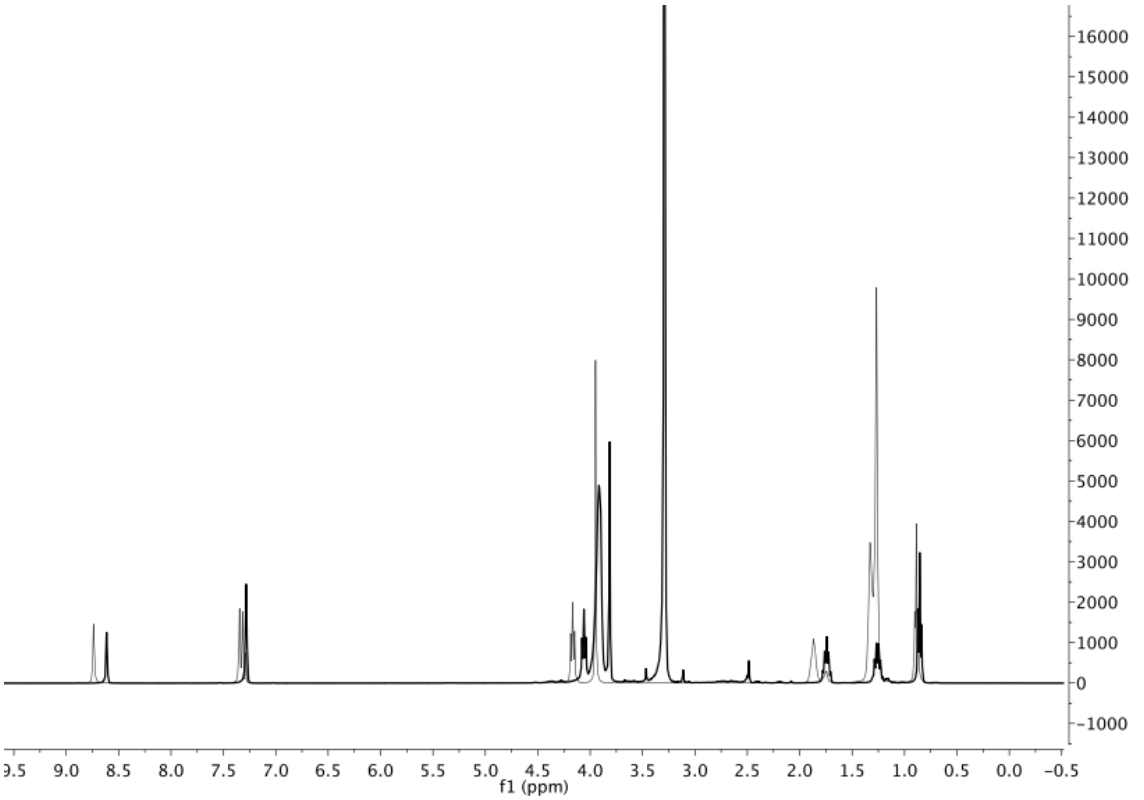

Figure 4.5- ^{1}H-NMR of IL [Bmim]NTf$_2$ and original IL.

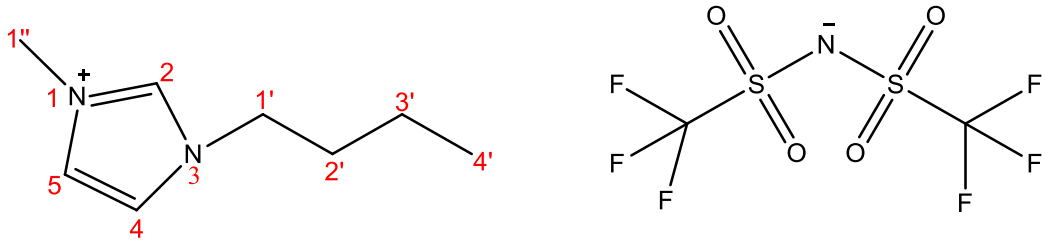

Figure 4.6- Atom numbering of [Bmim]NTf$_2$ for NMR analysis.

According to the structure of [Bmim]NTf$_2$, Figure 4.6, it is possible to calculate the total number of protons as 15.

The solvent signal is not visible because it is overlapped with one signal from the IL but it is known that it should appear at δ 7.26 ppm.[41]

The first signal identified was the signal at δ 0.85 ppm, integrating 3 protons, which corresponds to H-4', and consists in a triplet due to its coupling with H-3', presenting a J=6.1 Hz. The signal of H-3' should be a sextet since it couples with H-2' and H-4'. The signal at δ 1.26 ppm is a sextet that integrates 2 protons, therefore corresponds to the signal of H-3', and has a constant of coupling of J=6.8 Hz and J=15.31 Hz. The signal of H-2' at δ 1.74 ppm, with J=7.5 Hz and J=15.3 Hz, appears as a quintet due to the coupling with 4 protons, from H-1' and H-3'. At δ

4.06 ppm appears a triplet, integrating 2 protons, meaning that it corresponds to H-1', with J=7.5 Hz.

The signal of H-1'' is easily identifiable because it should be a singlet due to the inexistence of neighbor protons. At δ 3.81 ppm a singlet integrating 3 protons can, therefore, be assigned to H-1''.

Regarding the protons from the imidazolium ring, the signal of H-2 should be presented as a singlet, and H-4 and H-5 should be presented as two doublets. In the spectrum, it is shown a singlet at δ 8.61 ppm corresponding to H-2, and a doublet (integrating 2 protons) at δ 7.28 ppm corresponding to H-4 and H-5, with J=1.8 Hz and J=3.4 Hz. These two signals overlap because they are chemically identical.

In summary, all the signals were identified and assigned, confirming the structure of [Bmim]NTf_2. No other significant signals appear in the baseline resulted from an impurity, the only signal that appears is the signal at δ 3.29 ppm, corresponds to methanol, meaning that the ionic liquid still contains residues of methanol, so evaporation of methanol is required before its reuse. It is possible to conclude that the recovery of the IL after the reaction was successfully accomplished and IL might be reused in future reactions.

[Bmim]NTf_2 (3): ^{1}H-NMR ($CDCl_3$), δ (ppm) 0.85 (t, 3H, J=6.1 Hz, H-4'); 1.26 (sextet, 2H, J=6.8 Hz J=15.3 Hz, H-3'); 1.74 (quintet, 2H, J=7.5 Hz J=15.3, H-2'); 3.81 (s, 3H, H-1''); 4.06 (t, 2H, J=7.43 Hz, H-1'); 7.28 (d, 2H, J=1.8 Hz J=3.4 Hz, H-4 H-5); 8.61 (s, 1H, H-2). **^{13}C-NMR ($CDCl_3$), δ (ppm)** 12.9; 19.1; 28.9; 31.7; 35.9; 49.7; 119.5; 119.6; 122.9; 135.7.

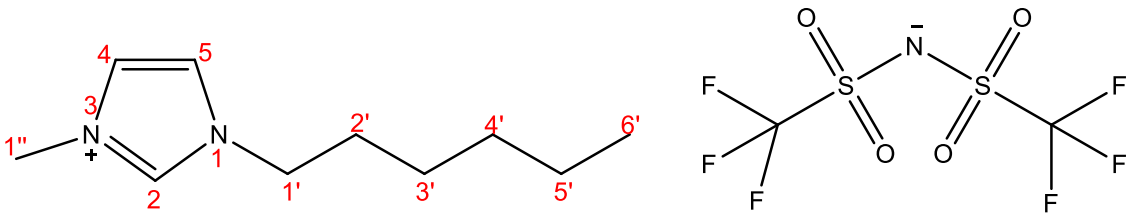

Figure 4.7. Atom numbering of [C6mim]NTf_2 for NMR analysis.

According to the structure of [C6mim]NTf_2, Figure 4.7, it is possible to calculate the total number of protons as 19.

The solvent signal appears at δ 7.26 ppm.[41]

The signal at δ 0.86 ppm is easily assigned to H-6', because it consists in a triplet due to its coupling with H-5' and the signal integrates 3 protons, with J=6.1 Hz.

The signal H-5’ should be a sextet since it couples with 5 protons from H-4’ and H-6’, and the signals of H-3’ and H-4’ should be two quintets integrating 2. These three signals coupled resulting in a large signal that integrates 6 protons, at δ 1.29 ppm.

The signal of H-1’ at δ 4.14 ppm, appears as a triplet due to the coupling with 2 protons, from H-2’ and integrates 2 protons, with J=7.6 Hz.

The signal of H-1’’ is easily identifiable because it should be a singlet due to the inexistence of neighboring protons. At δ 3.92 ppm a singlet integrating 3 protons can, therefore, be assigned to H-1’’.

Regarding the protons from the imidazolium ring, the signal of H-2 should be presented as a singlet, and H-4 and H-5 should be presented as doublets. In the spectrum, it is shown a singlet at δ 8.71 ppm corresponding to H-2, and a duplet that integrates 2 protons at δ 7.31 ppm corresponding to H-4 and H-5. These two signals overlap because they are chemically identical and have a coupling constant of J=6.7 Hz.

At δ 1.84 ppm appears a quintet integrating 2 protons, corresponding to H-2’, with a coupling constant J=13.8 Hz.

Is possible to conclude that the signals were identified and assigned, confirming the structure of [C6mim]NTf_2. In the baseline at δ 2.16 ppm appears an impurity, meaning that is necessary another step of extraction/purification of the IL to eliminate completely this impurity before the reuse of [C6mim]NTf_2 in future reactions.

[C6mim]NTf_2 (4): ^{1}H-NMR ($CDCl_3$), δ (ppm) 0.85 (t, 3H, J=6.1 Hz, H-6’); 1.29 (br s, 6H, H-3’ H-4’ H-5’); 1.84 (quintet, 2H, J=13.8 Hz, H-2’); 3.92 (s, 3H, H-1’’); 4.14 (t, 2H, J=7.6 Hz, H-1’); 7.31 (d, 2H, J=6.7 Hz, H-4 H-5); 8.71 (s, 1H, H-2). **^{13}C-NMR ($CDCl_3$), δ (ppm)** 13.8; 22.3; 25.7; 29.9; 30.9; 36.3; 50.2; 119.7; 119.8; 122.9; 135.9.

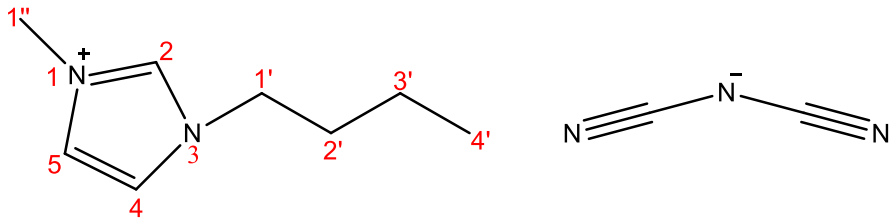

Figure 4.8- Atom numbering of [Bmim]DCA for NMR analysis.

As it is possible to calculate from the structure of [Bmim]DCA, Figure 4.8, the total number of protons is 15.

In the proton spectrum the solvent signal appears at δ 7.26 ppm.[41]

The first signal identified was the signal at δ 1.01 ppm which corresponds to H-4', that consists in a triplet due to its coupling with H-3', and integrates 3 protons with a coupling constant of J=6.9 Hz. The signal of H-1' should appear as a triplet, but in the spectrum, is presented as a multiplet at δ 3.90 to 3.95 ppm, integrating 2 protons. The same happened with the signal of H-2', that should be a quintet but the signal is not well defined and appears as a multiplet at δ 1.87 to 1.91 ppm integrating 2 protons.

The signal of H-3' should be a sextet but is presented as a quartet that integrates 2 protons, at δ 1.40 ppm, with J=7.2 Hz and J=15.8 Hz.

At δ 3.37 ppm appears a singlet integrating 3 protons, and this signal was easily assigned to H-1''.

Regarding the imidazolium protons, the signal of H-4 and H-5 should be presented as doublets, but they appear as singlets, each one integrating 1 proton, assigning the signal at δ 7.59 ppm to H-4, and the signal at δ 7.65 ppm to H-5. The signal of H-2 appears at δ 8.57 ppm as a singlet, integrating 1 protons, as it will be expected, due to its proximity to two nitrogen atoms.

In summary, all the signals were identified and assigned, confirming the structure and purity of [Bmim]DCA. Therefore, recovery of the IL after the reaction was successfully accomplished and IL might be reused in future reactions.

[Bmim]DCA (5): ^{1}H-NMR ($CDCl_3$), δ (ppm) 1.01 (t, 3H, J=6.9 Hz, H-4'); 1.40 (q, 2H, J=7.2 Hz J=15.8 Hz, H-3'); 1.87-1.91 (m, 2H, H-2'); 3.37 (s, 3H, H-1''); 3.90-3.95 (m, 2H, H-1'); 7.59 (s, 1H, H-5); 7.65 (s, 1H, H-4); 8.57 (s, 1H, H-2). **^{13}C-NMR ($CDCl_3$), δ (ppm)** 12.3; 19.0; 31.7; 35.1; 49.2; 117.8; 119.8; 122.2; 123.4; 136.3.

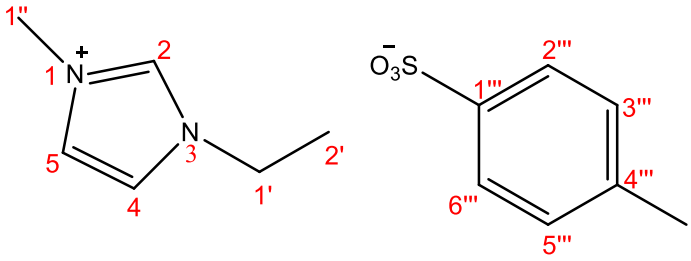

Figure 4.9- Atom numbering of [Emim]OTs for NMR analysis.

Analyzing the structure of [Emim]OTs, Figure 4.9, it was possible to calculate the total number of protons as 18.

Again the solvent signal appear at δ 7.26 ppm.[41]

The first signal identified was the signal at δ 1.38 ppm, integrating 3 protons, which corresponds to H-2'. It consists in a triplet due to its coupling with H-1', and the signal has a coupling constant of J=7.4 Hz.

The signal of H-2 was easily identifiable because it should be a singlet due to the inexistence of neighboring protons and it is known that it should be downfield due to the neighboring nitrogen atoms. Therefore, at δ 9.39 ppm a singlet integrating 1 proton can, therefore, be assigned to H-2.

The signal of H-1' should be a quartet since it couples with 3 protons from H-2', the quartet at δ 4.15 ppm with J= 7.4 Hz and J=14.7 Hz corresponds, unequivocally to H-1'.

According to Figure 4.9, the proton spectrum should present two singlets integrating 3 protons each, H-1'' and CH_3-4'''. In fact, in the spectrum is present one singlet at δ 3.85 ppm and another at δ 2.30 ppm. Similarly to the analysis of [Emim]OAc spectrum, it was possible to conclude that the first corresponds to H-1'' and the later to the aromatic CH_3 group

There are three doublets downfield in this spectrum, each one integrating 2 protons. According to the others NMR spectra it was possible to assign the signal at δ 7.34 ppm with J=7.8 Hz to the imidazolium ring protons H-4 and H-5. Therefore, the other 2 doublets correspond to the aromatic ring of tosylate group. The protons H-2''' and H-6''' are chemically identical and their signal should have a higher chemical shift compared with H-3''' and H-5''', due to their proximity to the SO_3 group. Hence, at δ 7.70 ppm with J=7.9 Hz is showed the signal of H-2''' and H-6''', and at δ 7.11 ppm with J=7.8 Hz, is showed the signals of H-3''' and H-5'''.

All the signals were identified, confirming the structure of [Emim]OTs. Since no other significant signals appear in the baseline resulted from an impurity, it is possible to conclude that the recovery of the IL after the reaction was successfully accomplished and IL might be reused in future reactions.

[**Emim]OTs (6): ^{1}H-NMR ($CDCl_3$), δ (ppm)** 1.38 (t, 3H, J=7.4 Hz, H-2'); 2.30 (s, 3H, CH_3-4'''); 3.85 (s, 3H, H1''); 4.15 (q, 2H, J=7.4 Hz J=14.7 Hz, H-1'); 7.11 (d, 2H, J=7.8 Hz, H-3''' H-5'''); 7.34 (d, 2H, J=7.8 Hz, H-4 H-5); 7.70 (d, 2H, J=7.9 Hz, H-2''' H-6'''); 9.39 (s, 1H, H-2). **^{13}C-NMR ($CDCl_3$), δ (ppm)** 15.3; 21.3; 36.2; 44.9; 121.7; 123.6; 125.8; 128.7; 136.9; 139.7; 143.3.

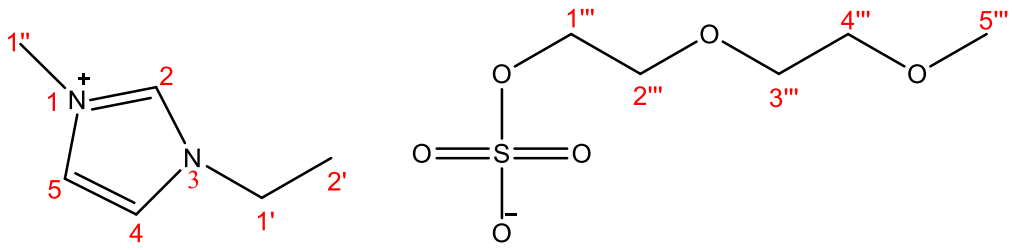

Figure 4.10- Atom numbering of [Emim]methoxy ethoxy ethyl sulfate for NMR analysis.

The structure of [Emim]methoxy ethoxy ethyl sulfate, Figure 4.10, shows that the total number of proton is 22, that means by integrating the signals, the total of the integration of all signals should be 22.

The solvent signal is visible and appear at δ 7.26 ppm.[41]

Similarly to the other analyses, the first signal identified was the signal of H-2' at δ 1.54 ppm which integrates 3 protons and consists in a triplet with J=7.3 Hz due to its coupling with H-1'. The signal H-2 should be a singlet downfield in the spectrum, since does not have protons in its neighboring. The signal at δ 9.36 ppm is a singlet that integrates 1 proton, therefore corresponds to the signal of H-2. The signal H-4 and H-5 should be presented as two doublets. In the spectrum, it is shown a doublet at δ 7.36 ppm, with J=7.11 Hz, corresponding to H-4 and H-5, integrating 2 protons, these two signals overlap because they are chemically identical.

The signal of H-1' at δ 4.28 ppm, appears as a quartet due to the coupling with 3 protons, from H-2' and integrates 2 protons, this signal presents a constant of coupling of J=7.3 Hz and J=14.7 Hz.

In the proton spectrum of this IL, two singlets, integrating 3 protons each, are observed corresponding to either H-1'' or H-5''. In analogy with the analysis [Emim]OAc, the higher chemical shift must correspond to H-1'' due to the fact that CH_3 group is bonded to a nitrogen. Consequently, the signal at δ 3.98 ppm can be assigned to H-1'' and the signal at δ 3.45 ppm can be assigned to H-5'''.

At δ 4.16 ppm there is a triplet integrating 1 proton with J=4.8 Hz, and at δ 4.09 ppm there is a quartet integrating 1 proton with J=6.7 Hz and J=13.9 Hz, these to signals correspond to H-1''', but it should appear as triplet integrating 2 protons. From δ 3.50 ppm to δ 3.72 ppm there is a multiple, integrating 6 protons corresponding to H-2''', H-3''' and H-4''', that should appear in three different triplets integrating 2 protons each one.

In summary, all the signals were identified and assigned, confirming the structure of [Emim]methoxy ethoxy ethyl sulfate. It is possible to observe in the spectrum that are present other signals that do not belong to the structure of the IL, are therefore resulted from an impurity. An extra purification step might be required it reuse of this IL is desired.

[**Emim]methoxy ethoxy ethyl sulfate (7): ^{1}H-NMR ($CDCl_3$), δ (ppm)** 1.54 (t, 3H, J=1.5 Hz, H-2'); 3.45 (s, 3H, H-7'''); 3.50 to 3.72 (m, 6H, H-2''' H-4''' H-5'''); 3.98 (s, 3H, H-1''); 4.09 (q, 1H, J=6.7 Hz J=13.9 Hz, H-1'''); 4.16 (t, 1H, J=4.8 Hz, H-1'''); 4.28 (q, 2H, J=7.3 Hz J=14.7 Hz, H-1'); 7.36 (d, 2H, J=7.1 Hz, H-4 H-5); 9.36 (s, 1H, H-2). **^{13}C-NMR ($CDCl_3$), δ (ppm)** 15.3; 36.4; 45.2; 58.8; 66.5; 69.9; 70.2; 71.8; 121.6; 123.5; 137.3.

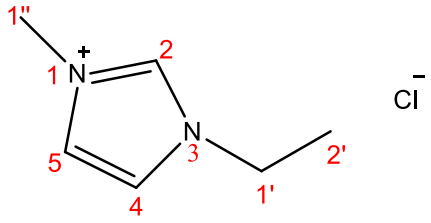

Figure 4.11- Atom numbering of [Emim]Cl for NMR analysis.

In Figure 4.11, is represented the structure of IL [Emim]Cl used in one of the reactions of this project. Based on this structure it is possible to calculate the total number of protons as 11.

Contrary to the others IL, [Emim]Cl required MeOD as solvent for NMR experiments due to poor solubility in $CDCl_3$. The signals of this solvent are visible at δ 4.80 ppm and δ 3.31 ppm.[41]

The first signal identified was the signal at δ 1.50 ppm, integrating 3 protons, which corresponds to H-2', it consists in a broad singlet, however it should appear as a triplet due to its coupling with 2 protons from H-1'.

The signal of H-2 proton at δ 8.98 ppm, can be easily recognizable since it should be a singlet due to the inexistence of protons in its surrounding and, integrating 1 proton.

The signal of H-4 is a singlet and appears at δ 7.63 ppm integrating 1 proton, and H-5 is shown also as singlet at δ 7.55 ppm integrating 1 proton. Again, these signals appear downfield in the spectrum due to the presence of the nitrogen atom adjacent to these protons.

The signal of H-1' should appear as a quartet due to the interaction with the protons of H-2', but instead appears as broad singlet integrating 2 protons, at δ 4.25 ppm

At δ 3.92 ppm a singlet is visible, integrating 3 protons, corresponding to H-1'', because these protons are the only protons that should produce a singlet integrating 3 protons.

In summary, all the signals were assigned, confirming the structure of [Emim]Cl. There is no other significant signal that could correspond to impurities in the spectrum, indicating that the recovery of the IL after the reaction was a success and the reuse of the IL in future reactions might be possible.

[**Emim]Cl (8): ^{1}H-NMR (MeOD), δ (ppm)** 1.50 (br s, 3H, H-2'); 3.92 (br s, 3H, H-1''); 4.25 (br s, 2H, H-1'); 7.55 (s, 1H, H-5); 7.63 (s, 1H, H-4); 8.98 (s, 1H, H-2). **^{13}C-NMR ($CDCl_3$), δ (ppm)** 14.4; 35.4; 44.8; 122.0; 123.1; 136.5.

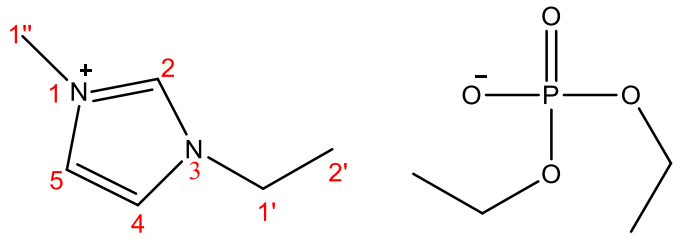

Figure 4.12- Atom numbering of [Emim]diethyl-phosphate for NMR analysis.

From the structure of [Emim]diethyl-phosphate, Figure 4.12, it was possible to calculate the total number of protons as 21.

The $CDCl_3$ signal was visible and appear at δ 7.26 ppm.[41]

The first signal identified was the signal at δ 7.39 ppm which corresponds to H-4 and the signal at δ 7.35 ppm that corresponds to H-5, they are two singlets, each one integrating 1 proton.

The signal of H-2 was readily identifiable, since it appeared as a singlet integrating 1 proton, at δ 9.79 ppm. These three signals are very distinctive, since they always appear downfield in the spectrum as explained earlier.

At δ 4.29 ppm is visible the signal of H-1' that consists in a quartet, with J=7.3 Hz and J=14.7 Hz, due to its coupling with H-2', integrating 2 protons. The signal at δ 3.96 ppm is a singlet that integrates 3 protons, therefore corresponds to the signal of H-1''. The signal of H-2' is a triplet integrating 3 protons due to the interaction with H-1', the signal appears at δ 1.50 ppm with J=7.4 Hz.

The signals of both ethyl group in the phosphate anion appear at δ 3.89 ppm and δ 1.20 ppm, corresponding to the $–CH_2-$ and $–CH_3$ protons, respectively. The first is a quintet, although it should be a quartet, J=13.9 Hz and J=7.0 Hz; the second is a triplet, integrating 6 protons and with J=7.0 Hz.

Once again, all the signals were identified and assigned, confirming the structure of [Emim]diethyl-phosphate. It was possible to observe in the spectrum that exists other signals that do not belong to the structure of the IL, hence resulting from an impurity or remaining of solvent. Further purification of this IL might be necessary if reuse is desired.

[**Emim]diethyl-phosphate (9): ^{1}H-NMR ($CDCl_3$), δ (ppm)** 1.20 (t, 6H, J=7.0 Hz, $POCH_2C\underline{H}_3$); 1.50 (t, 3H, J=7.4 Hz, H-2'); 3.89 (quintet, 4H, J=13.9 Hz J=7.0 Hz, $POC\underline{H}_2CH_3$); 3.96 (s, 3H, H-1''); 4.29 (q, 2H, J=7.3 Hz J=14.7 Hz, H-1'); 7.35 (s, 1H, H-5); 7.39 (s, 1H, H-4); 9.79 (s, 1H, H-2). **^{13}C-NMR ($CDCl_3$), δ (ppm)** 15.4; 16.5; 16.6; 36.3; 44.9; 61.0; 69.9; 121.0; 123.5; 137.9.

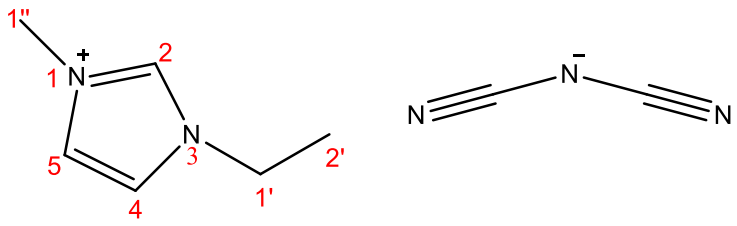

Figure 4.13- Atom numbering of [Emim]DCA for NMR analysis.

The structure of [Emim]DCA, Figure 4.13, allows the calculation of total number of protons as being 11.

Similarly to the IL [Emim]Cl, [Emim]DCA required MeOD as solvent for NMR experiments due to poor solubility in $CDCl_3$. The signals of this solvent are visible at δ 4.80 ppm and δ 3.31 ppm.[41]

The signal of H-2' was the first to be assigned, since it is a triplet integrating 3 protons, appearing at δ 1.54 ppm, with the coupling constant of J=7.2 Hz.

The signal at δ 4.27 ppm is a quartet, with J=7.4 Hz and J=14.4 Hz, that integrates 2 protons, being easily assigned to H-1'.

In the spectrum are presented four signals as singlets. At δ 7.65 ppm corresponding to H-4, and at δ 7.57 ppm the signal was assigned to H-5, both signals integrate 1 proton. The last signal presented as singlet integrating 1 proton, appears at δ 8.57 ppm and corresponds to H-2.

At δ 3.94 ppm is presented the signal of H-1'', appears as a singlet integrating 3 protons, as expected.

[**Emim]DCA (10): ^{1}H-NMR (MeOD), δ (ppm)** 1.54 (t, 3H, J=7.2 Hz H-2'); 3.94 (s, 3H, H-1''); 4.27 (q, 2H, J=7.4 Hz J=14.4 Hz, H-1'); 8.57 (s, 1H, H-2); 7.57 (s, 1H, H-5); 7.65 (s, 1H, H-4). **^{13}C-NMR ($CDCl_3$), δ (ppm)** 14.2; 35.0; 44.6; 121.9; 123.5; 136.4; 162.0.

Some signals are not properly resolved in the presented spectra, and this can be due to the equipment used in these analyses or even because of the possibility that some ILs are not totally soluble in the solvent utilized.

Although the protocol of ionic liquid recovery was exactly the same for all, the [C6mim]NTf_2 was the IL recovered with less impurities, as it is possible to confirm by analyses of the spectra in Appendix section where the proton NMR of the used IL is superimposed with the non-used IL.

A carbon experiment was performed for each ionic liquid used as well as the non-used ILs to evaluate the purity of the recovered IL. Nevertheless, in all cases all carbons are accounted for, although it is not possible to do the individual assignment due the lack of other experiments that would be required for that.

4.3 HPLC

High-pressure liquid chromatography (HPLC) analyses were performed to obtain the percentage of malic acid conversion. Along with the selectivity calculated from GC, it is possible to calculate the yield of each product formed, using following equations, according to literature.[42]

$$Conversion\ of\ Malic\ Acid\ (\%) = \frac{moles\ of\ malic\ acid\ that\ reacted}{moles\ of\ malic\ acid\ supplied} \times 100 \quad (1)$$

$$S\ for\ product\ (\%) = \frac{moles\ of\ product\ formed}{moles\ of\ malic\ acid\ reacted} \times 100 \quad (2)$$

$$Y\ for\ product\ (\%) = \frac{conversion\ of\ malic\ acid \times S\ for\ product}{100} \quad (3)$$

Where, S is the selectivity and Y is the yield.

The conversion (%) of malic acid and yields (%) of each compound resulted from the hydrogenation reaction using Ru-based catalyst (pH_2=120 bar, T=393.15 K, final pressure p=180 bar, t=6 h) are presented in Table 4.4 according to equations 1 and 3, respectively.

Table 4.4- Conversion of malic acid and yield of products obtained in the hydrogenation of malic acid in ScCO2 using Ru-based catalyst.

Entry	Ionic Liquid	Conversion of Malic Acid (%)	Yield (%)					
			11	12	13	14	15	16
1	[Emim]OAc	100	-	31.0	69.0	-	-	-
2	[Bmim]NTf_2	99.02	23.2	-	-	36.5	27.6	11.7
3	[C_6mim]NTf_2	100	41.4	-	-	27.7	30.9	-

Similarly, the conversion (%) of malic acid and yields (%) of each compound resulted from the hydrogenation reaction using Pd-based catalyst (pH_2=60 bar, T=393.15 K, final pressure p=120 bar, t=20 h) are presented in Table 4.5 according to equations 1 and 3, respectively.

*Table 4.5- Conversion of malic acid and yield of products obtained in the hydrogenation of malic acid in ScCO2 using Pd catalyst. *This reaction was performed with pH_2=120 bar, total pressure p=180 bar and reaction time of 6 h.*

Entry	Ionic Liquid	Conversion of Malic Acid (%)	Yield (%)								
			12	13	14	15	16	17	18	19	20
1	[Bmim]DCA	100	-	-	-	-	-	-	15.2	-	-
2*	[Emim]OAc	100	30.2	65.2	-	-	-	-	-	2.8	-
3	[Emim]OAc	100	29.0	63.0	-	-	-	-	-	7.9	-
4	[Emim]OTs	100	-	-	32.9	54.1	13.0	-	-	-	-
5	[Emim]methoxy ethoxy ethyl sulfate	99.75	-	-	2.3	20.3	1.7	0.9	-	-	66.6
6	[Emim]Cl	100	1.8	-	49.3	17.1	1.0	7.6	-	-	23.2
7	[Emim]diethyl-phosphate	100	11.9	20.7	27.5	34.3	-	1.4	4.2	-	-

Malic acid was only quantified in two samples; first from the reaction where [Bmim]NTf_2 was used (entry 2, Table 4.4), with a conversion of 99.02%, second from the reaction where [Emim]methoxy ethoxy ethyl sulfate was used (entry 5, Table 4.5), with a conversion of 99.75%. However, the absence of malic acid on the remaining samples might be due to the dilution

required to perform the experiments. Hence, for calculations purposes, a 100% conversion was considered.

4.4 TEM

Nanoparticle catalysts have a higher activity and selectivity, since they present high surface to bulk metal ratio permitting a more efficiency use. Because their kinetical instability due to the agglomeration to the bulk metal, before the use, there is the need of stabilization, his can be obtained by surface-ligating anions or other ligands.

According to literature it has been showed that after stabilization with ionic liquids, nanometallic catalysts are activated. Ionic liquids are used in these syntheses, due to their highly polar starting materials that facilitates inorganic synthesis, under anhydrous or water-poor conditions.[43]

This might explain the possible *in situ* formation of nanoparticle catalysts during the reaction of hydrogenation of malic acid using ILs.

To confirm if nanoparticles were formed during the hydrogenation reactions, TEM (Transmission Electron Microscopy) analyses were performed after the reaction in [Emim]OAc and in [Bmim]NTf_2 as indicated in Table 4.1, entry 1 and 2, respectively.

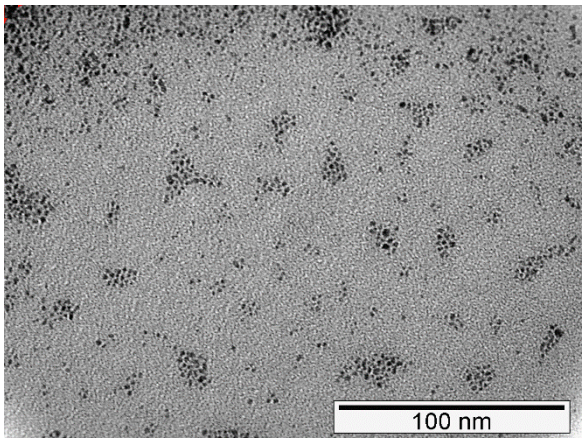

Figure 4.14- TEM image of Ruthenium catalyst of the reaction of entry 1, Table 4.1.

As mentioned in the methods section, after the reaction catalysts were recovered by filtration, washed and dried. Interestingly after the reaction in [Emim]OAc the catalyst was hardly recovered as it passed through the filter, suggesting the formation of nanoparticles. In fact, according to the above TEM image, Figure 4.14, the ruthenium nanoparticles were actually formed and their sizes were calculated to be 1.5-2.5 nm. However, the catalyst after the reaction

in [Bmim]NTf_2 was much easier to recover suggesting the non-formation of nanoparticles or highly aggregated nanoparticles. TEM analysis confirmed the second option as the nanoparticles were formed, with 2.5 nm in size, but were highly aggregated as showed in Figure 4.15.

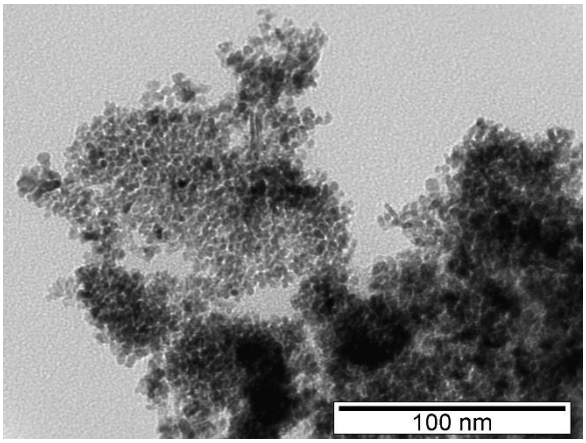

Figure 4.15- TEM image of Ruthenium catalyst of the reaction of entry 2, Table 4.1.

The very large surface area of the nanoparticles causes them to aggregate, as showed by TEM analysis, depending on the ionic liquid the level of aggregation may vary. Nanoparticles are only kinetically stable, and they should be stabilized against aggregation. There are reports showing that the use of ILs may act as stabilizers and immobilizers of the nanoparticles, avoiding the aggregation of these nanoparticles; showing that possibly, the IL used in the reactions, may influence the formation of aggregates.[44]

5. Conclusions

Comparing the results from reactions with different cation and the same anion, is possible to observe that the compounds formed were similar and with comparable selectivities.

Using ionic liquids with the same cation and different anion, the products formed were not exactly the same in all; but, when compounds were exactly the same, selectivities were slightly different. These results suggested that the structure of ionic liquids used might have a great impact on the type of compounds obtained.

In two samples taken from the reaction mixture, the conversion of malic acid was significantly high; however, all the other samples it was not possible to quantify the amount of malic acid and therefore a complete conversion was considered.

The influence of the reactions conditions, such as pressure of H_2, total pressure and the reaction time, were compared in three reactions using the same IL, but changing the reaction conditions and later the catalyst, Ru-based or Pd-based. The results showed that the influence of the conditions on the reaction is almost insignificant. With different catalyst, the selectivities were similar, but the minor compound was not formed when Ru-based catalyst was used. The parameter that seems to influence more the type of products and also their selectivities is the IL choice, more precisely, the anion type.

In overall, the ionic liquids used in the hydrogenation of malic acid were effectively recovered and with a high level of purity, showing that it might be possible its reuse in future reactions.

All catalysts were also recovered after the reactions, but further experiments are necessary to assess its reusability.

In summary, the goals of this project were successfully accomplished, however further optimizations and analyses are required to better understand the mechanism of the reaction and the influence of catalyst, ionic liquid and reaction conditions (such as H_2, CO_2 pressures and temperature) on the scope of the reaction.

6. Bibliography

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7. Appendix

In this appendix are the spectrums of ^{1}H-NMR and ^{13}C-NMR of all experiments.

Reaction with [Emim]OAc:

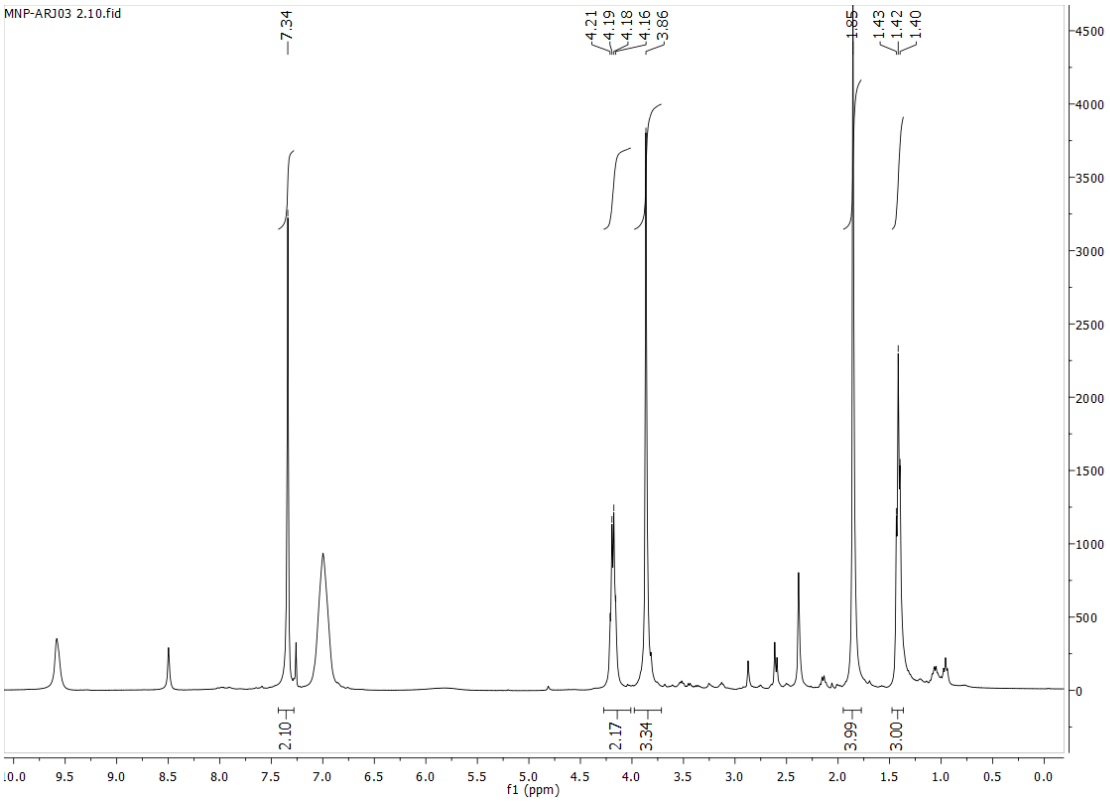

Figure 7.1- ^{1}H-NMR of [Emim]OAc after reaction.

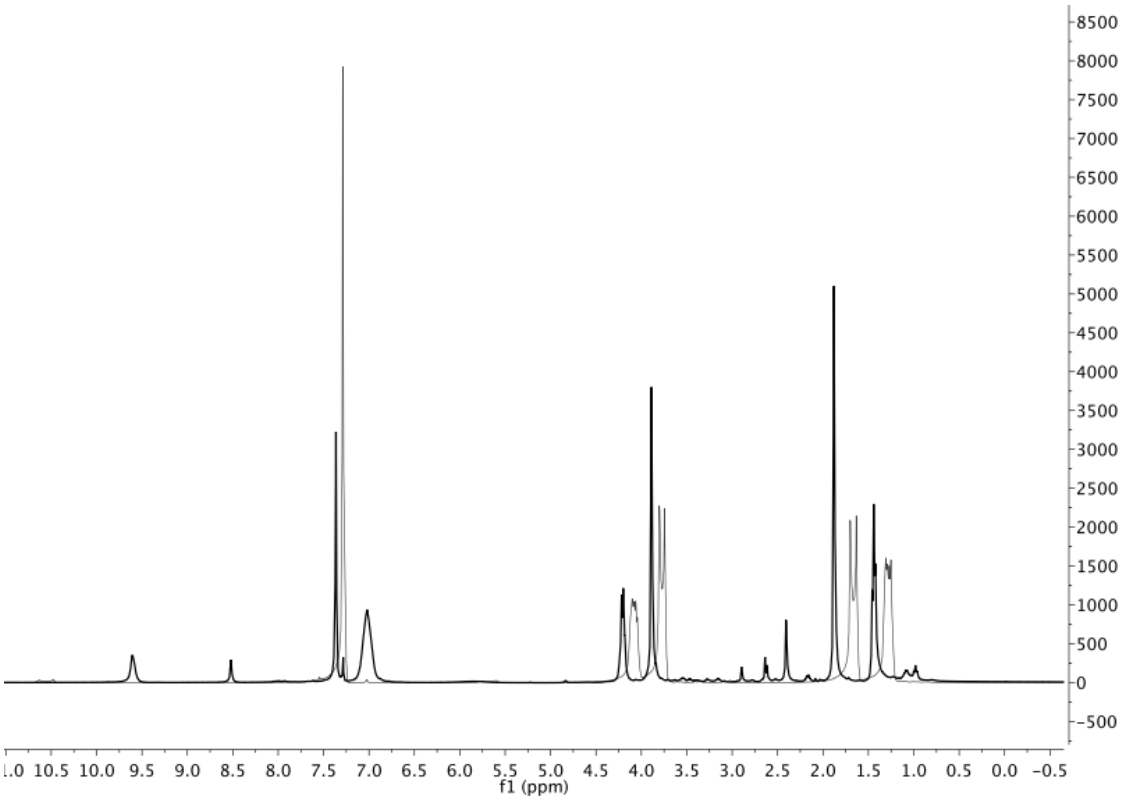

Figure 7.2- Comparison of [1]H-NMR of [Emim]OAc after reaction with original.

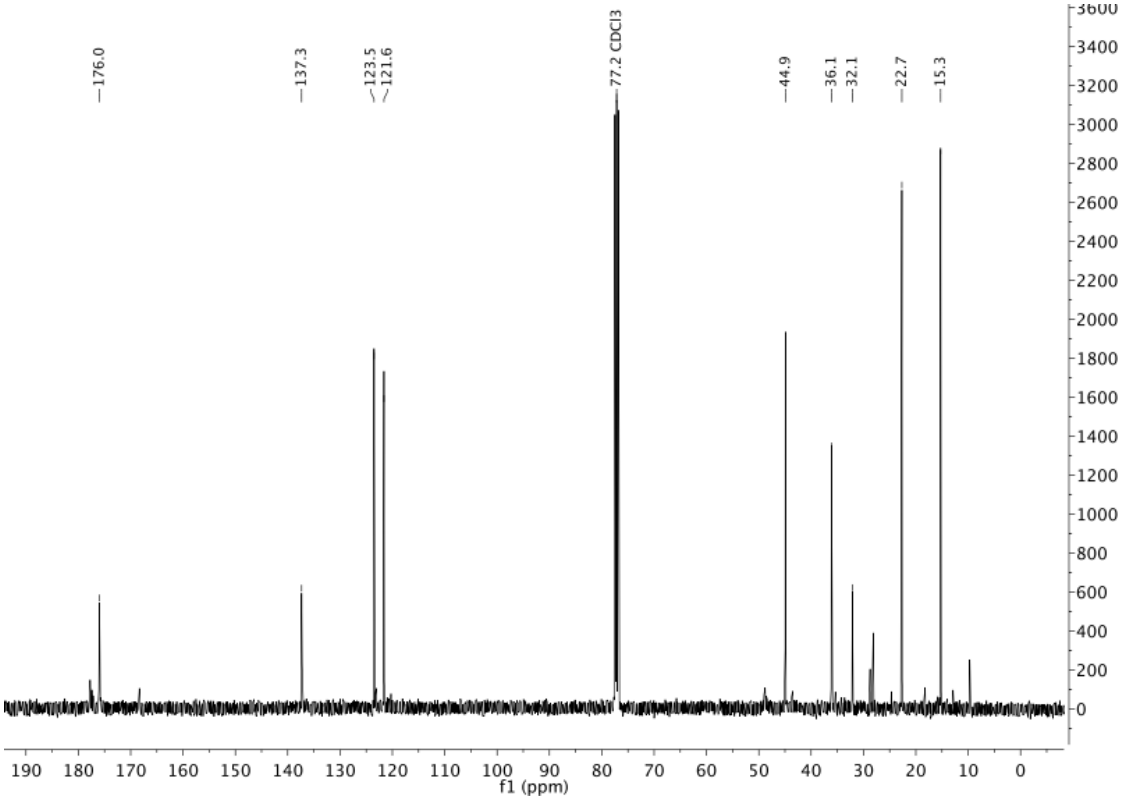

Figure 7.3- [13]C-NMR spectrum of [Emim]OAc after reaction.

Reaction with [Bmim]NTf_2:

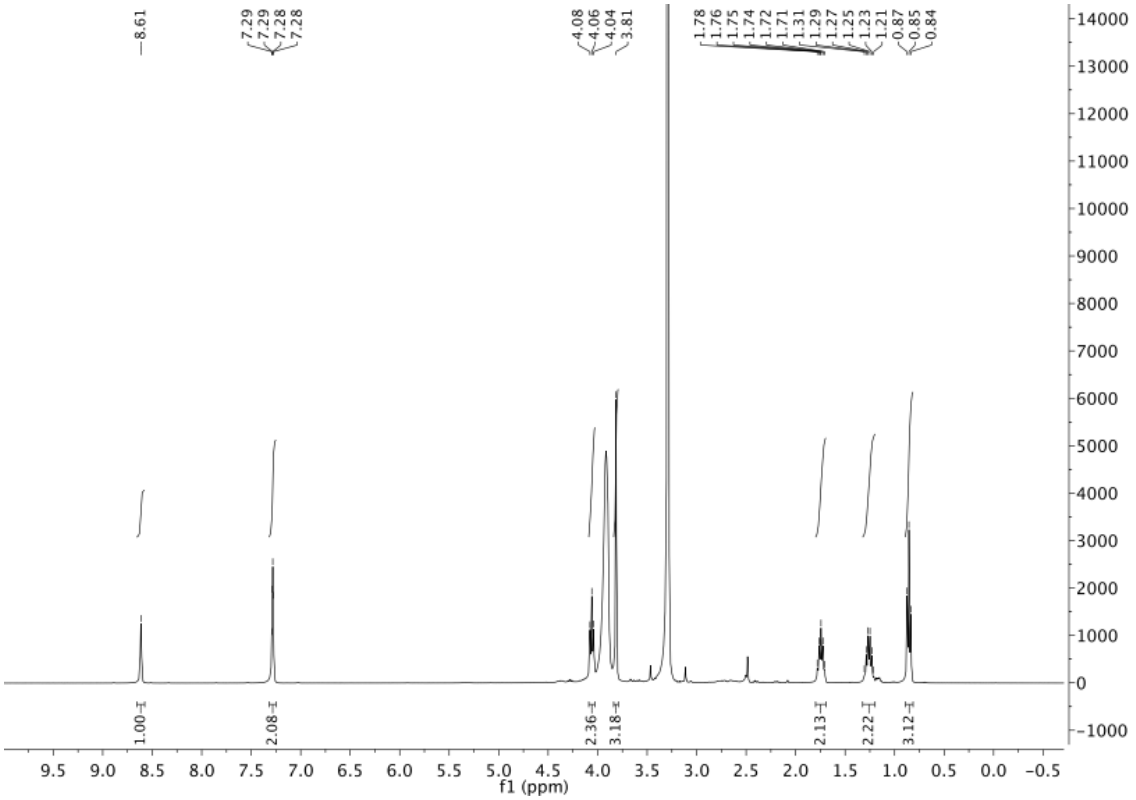

Figure 7.4- ^{1}H-NMR of [Bmim]NTf_2 after reaction.

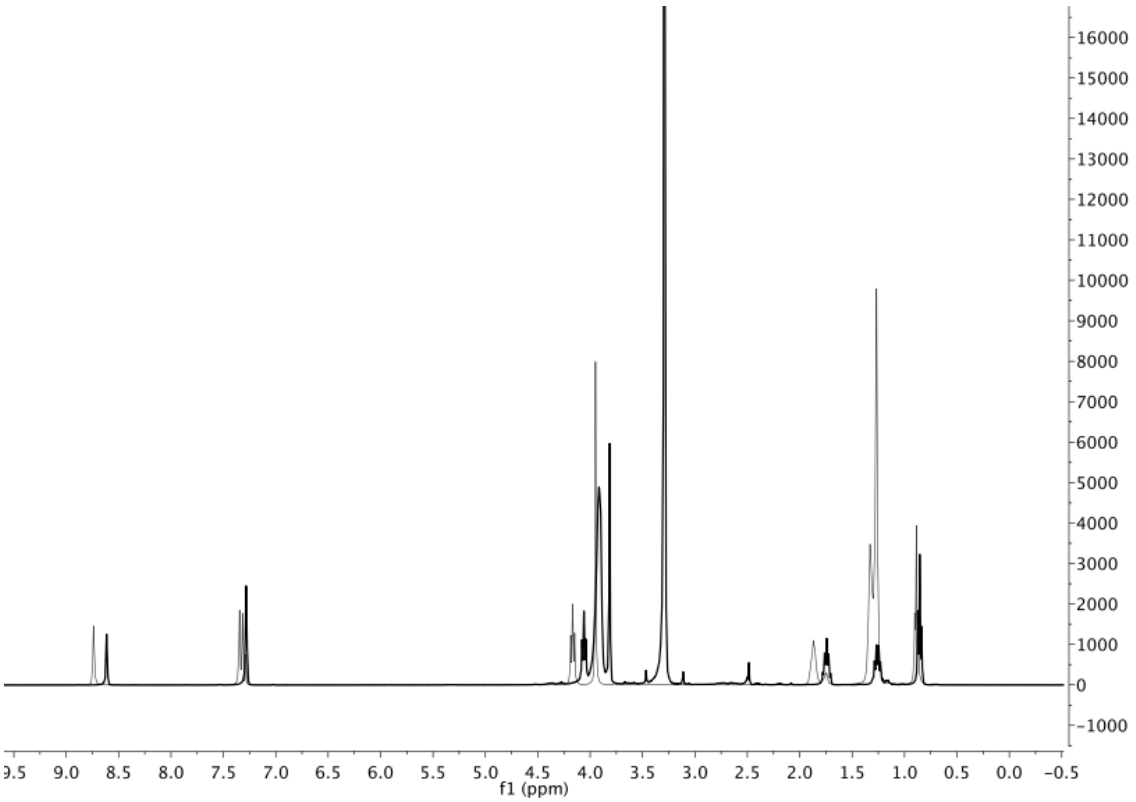

Figure 7.5- Comparison of ^{1}H-NMR of [Bmim]NTf_2 after reaction with original.

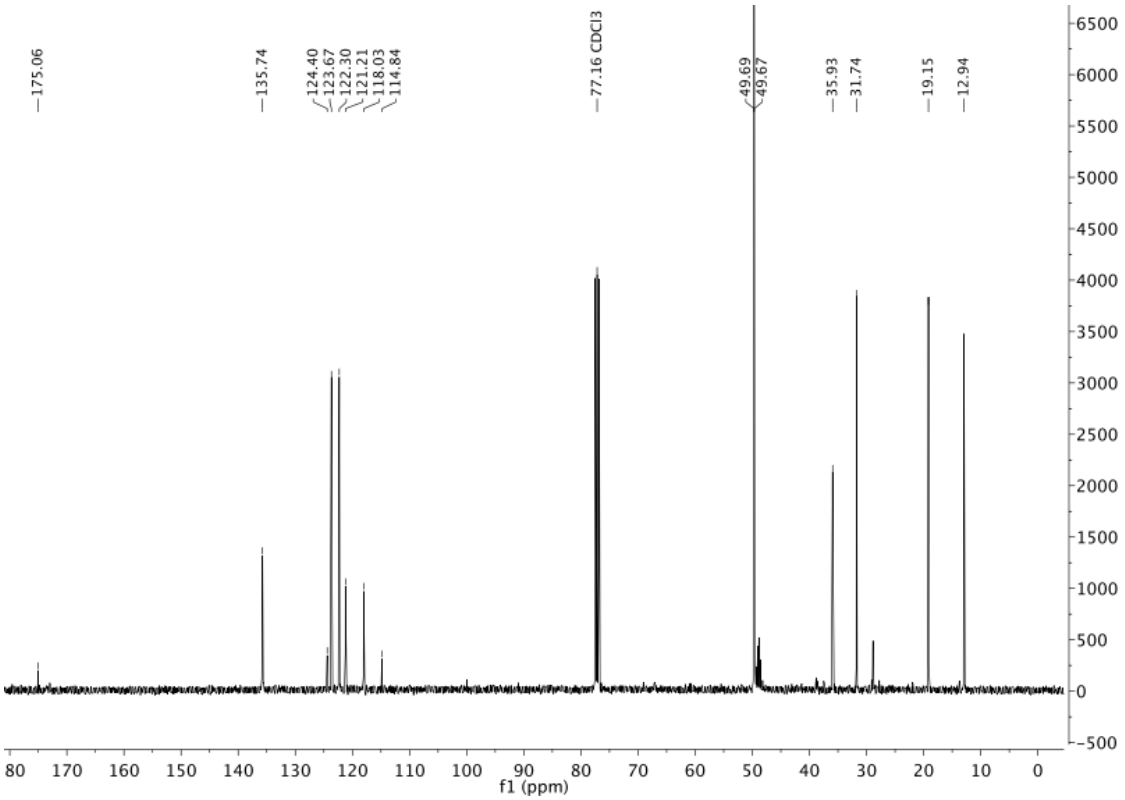

Figure 7.6- ^{13}C-NMR spectrum of [Bmim]NTf_2 after reaction.

Reaction with [C_6mim]NTf_2:

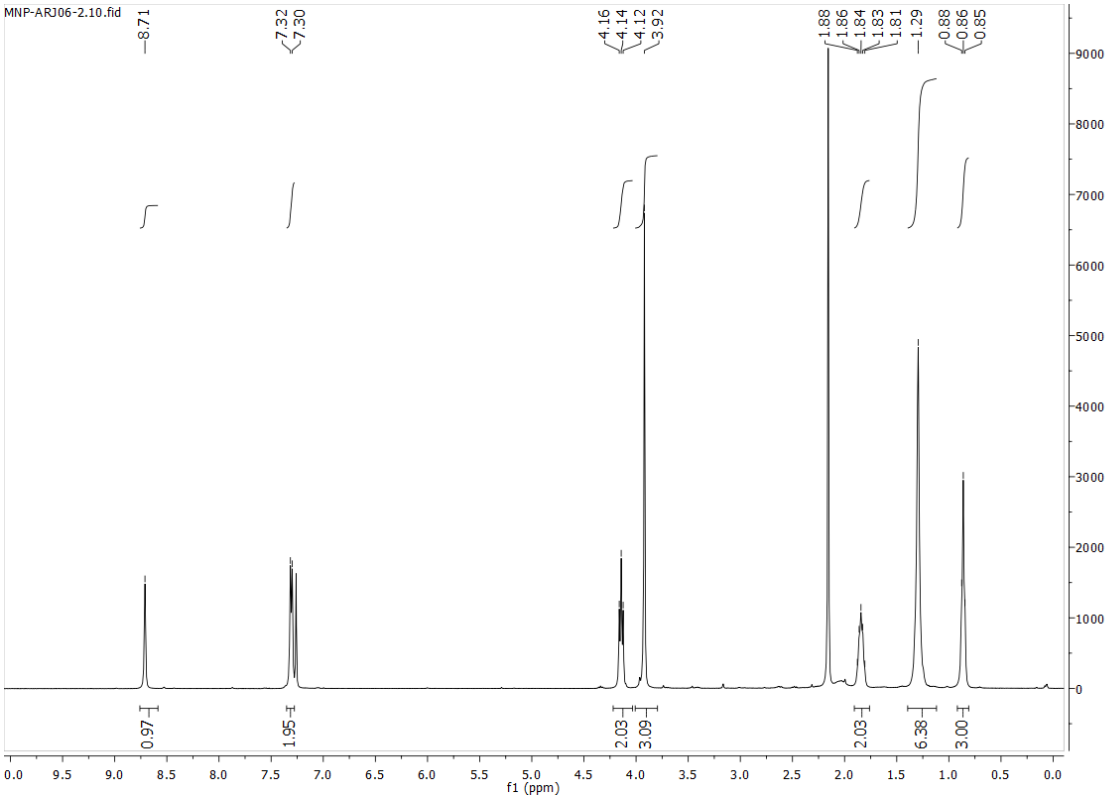

Figure 7.7- ^{1}H-NMR of [C_6mim]NTf_2 after reaction.

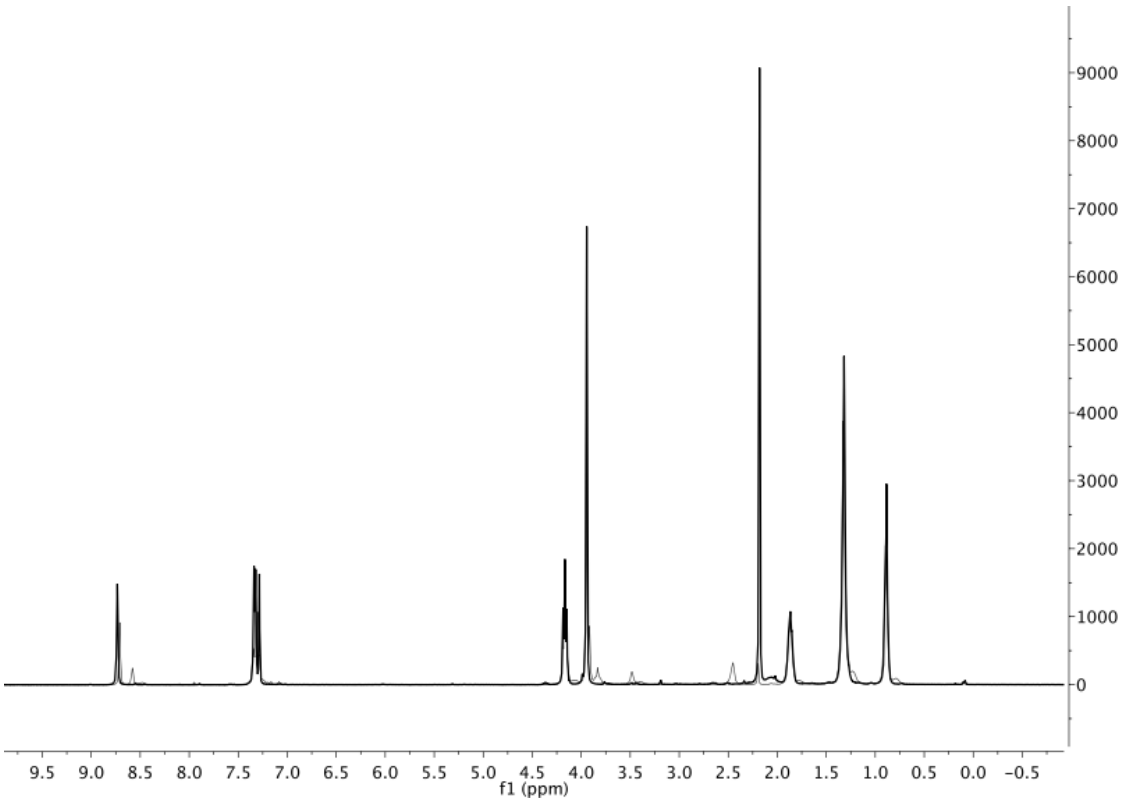

Figure 7.8- Comparison of ^{1}H-NMR of [C_6mim]NTf_2 after reaction with original.

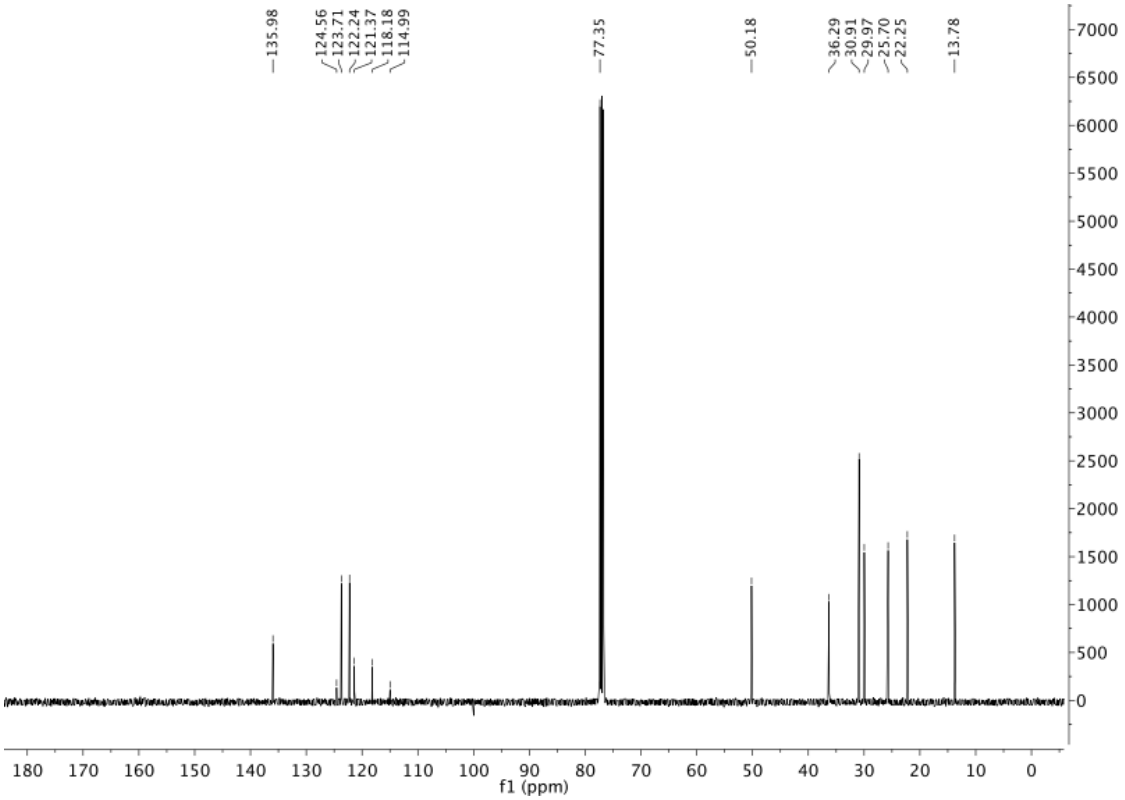

Figure 7.9- ^{13}C-NMR spectrum of [C_6mim]NTf_2 after reaction.

Reaction with [Bmim]DCA:

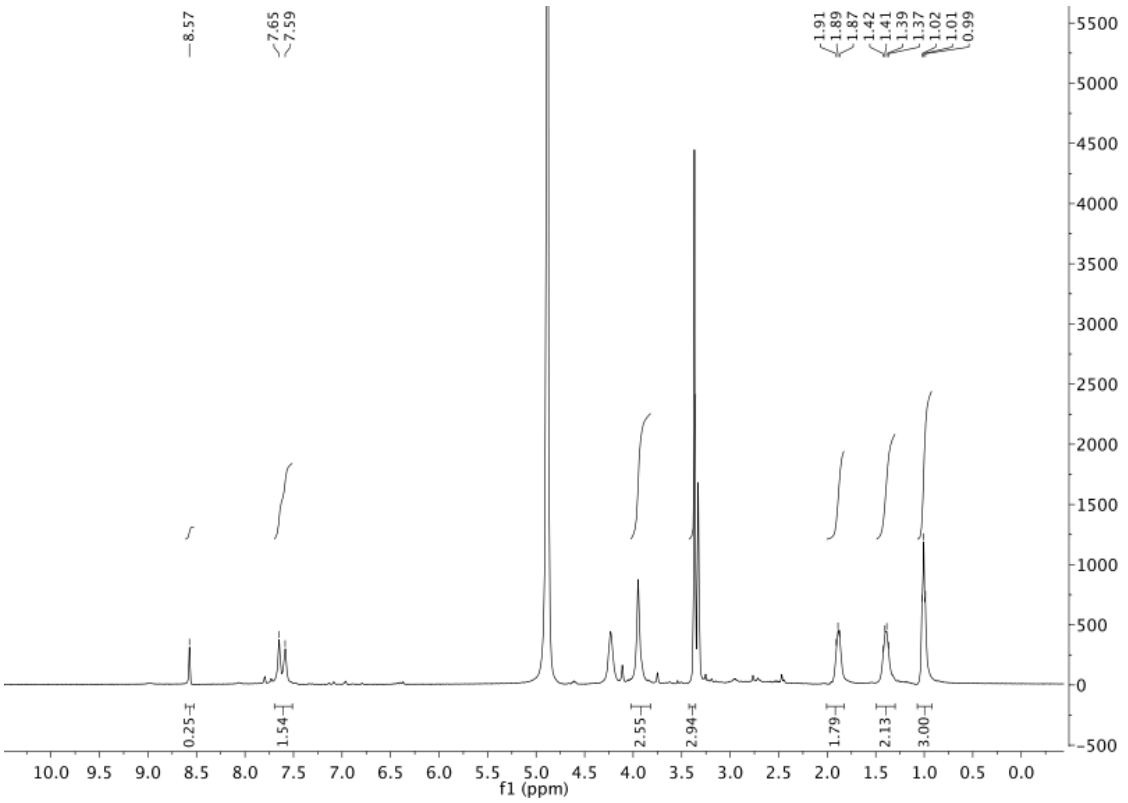

Figure 7.10-^{1}H-NMR of [Bmim]DCA after reaction.

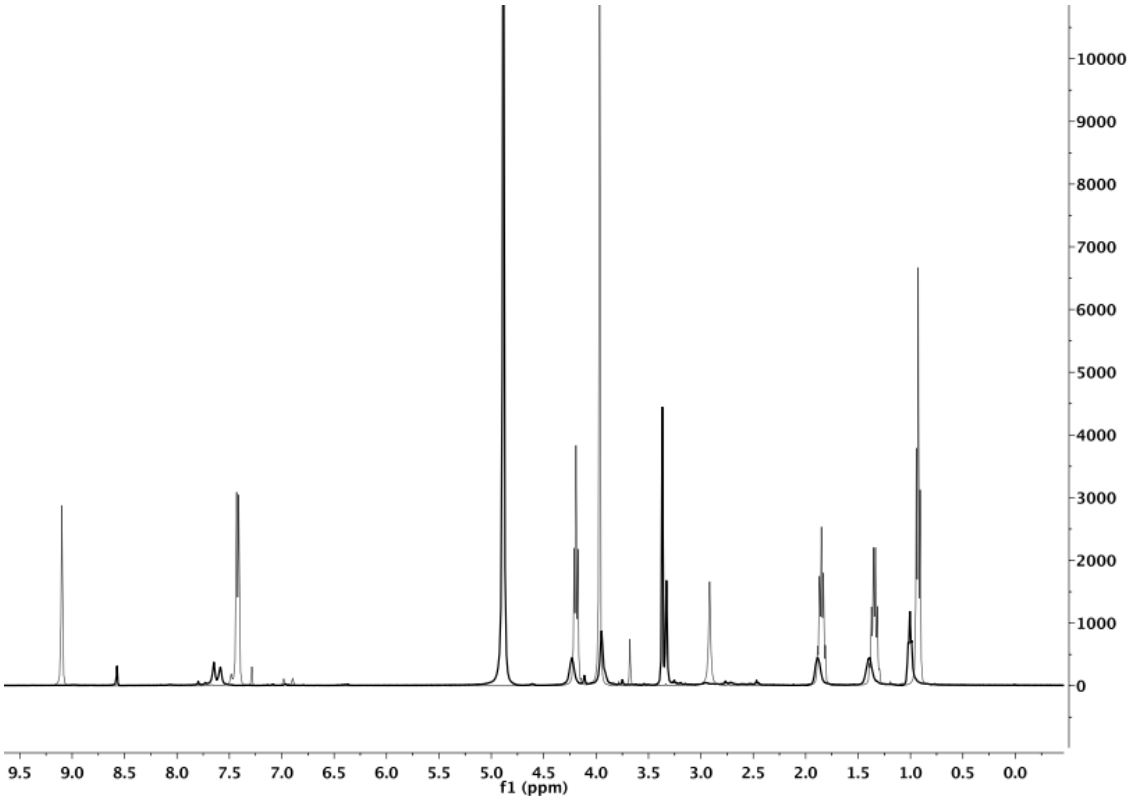

Figure 7.11- Comparison of ^{1}H-NMR of [Bmim]DCA after reaction with original.

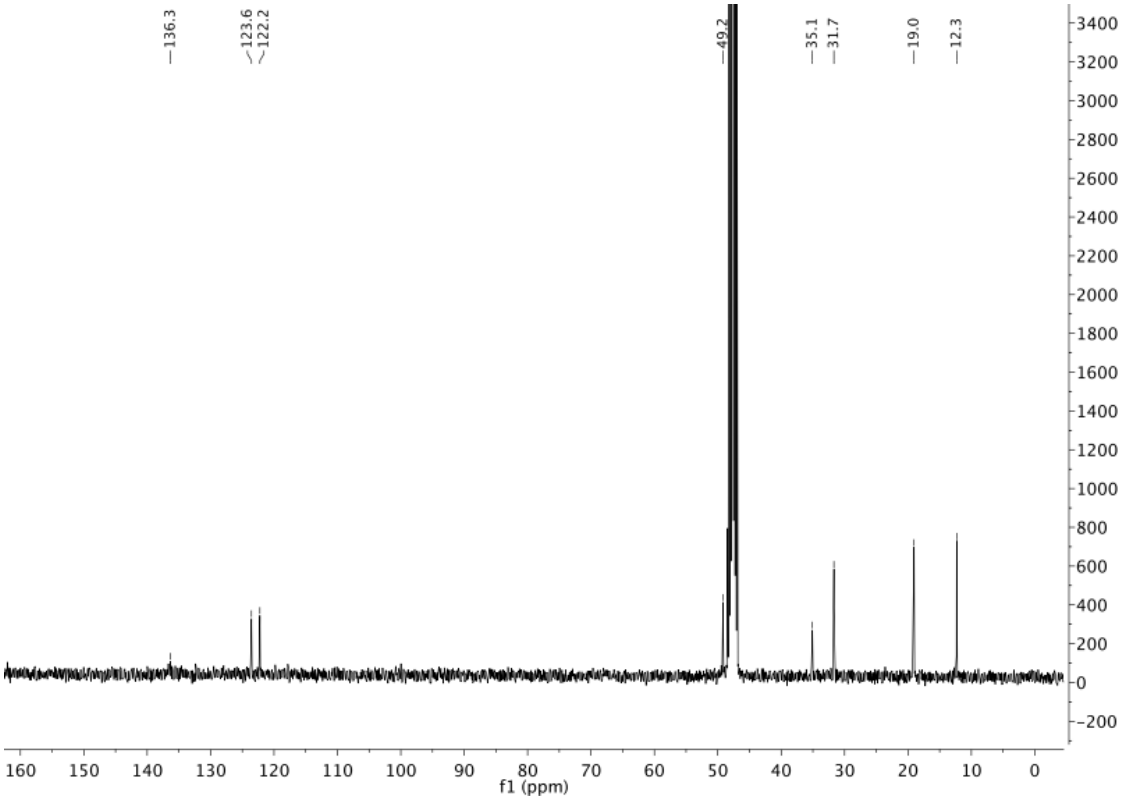

Figure 7.12- ^{13}C-NMR spectrum of [Bmim]DCA after reaction.

Reaction with [Emim]OTs:

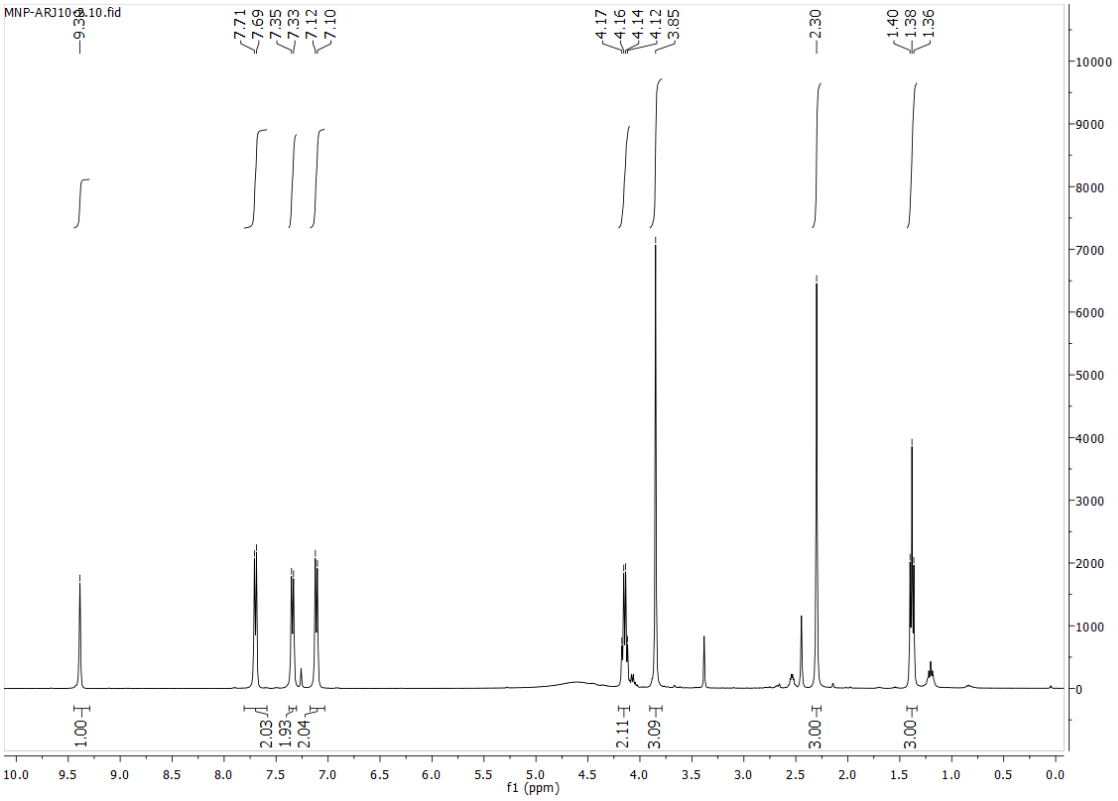

Figure 7.13- ^{1}H-NMR of [Emim]OTs after reaction.

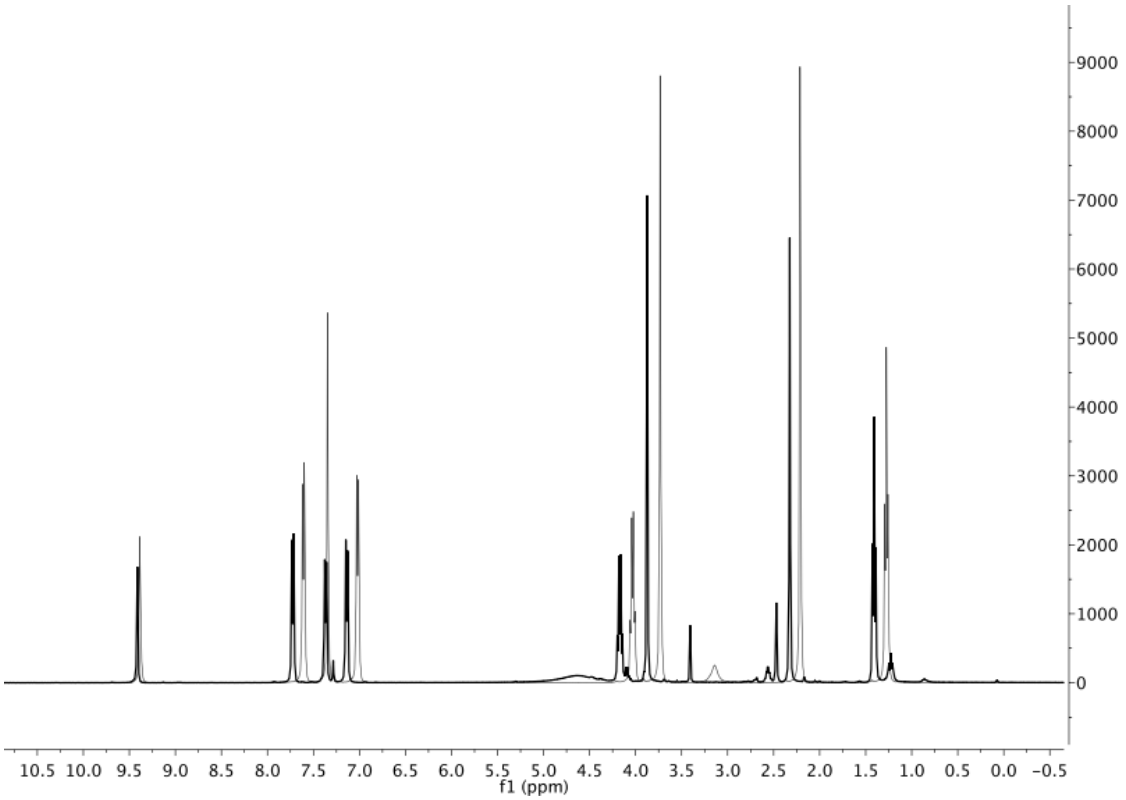

Figure 7.14- Comparison of ^{1}H-NMR of [Emim]OTs after reaction with original.

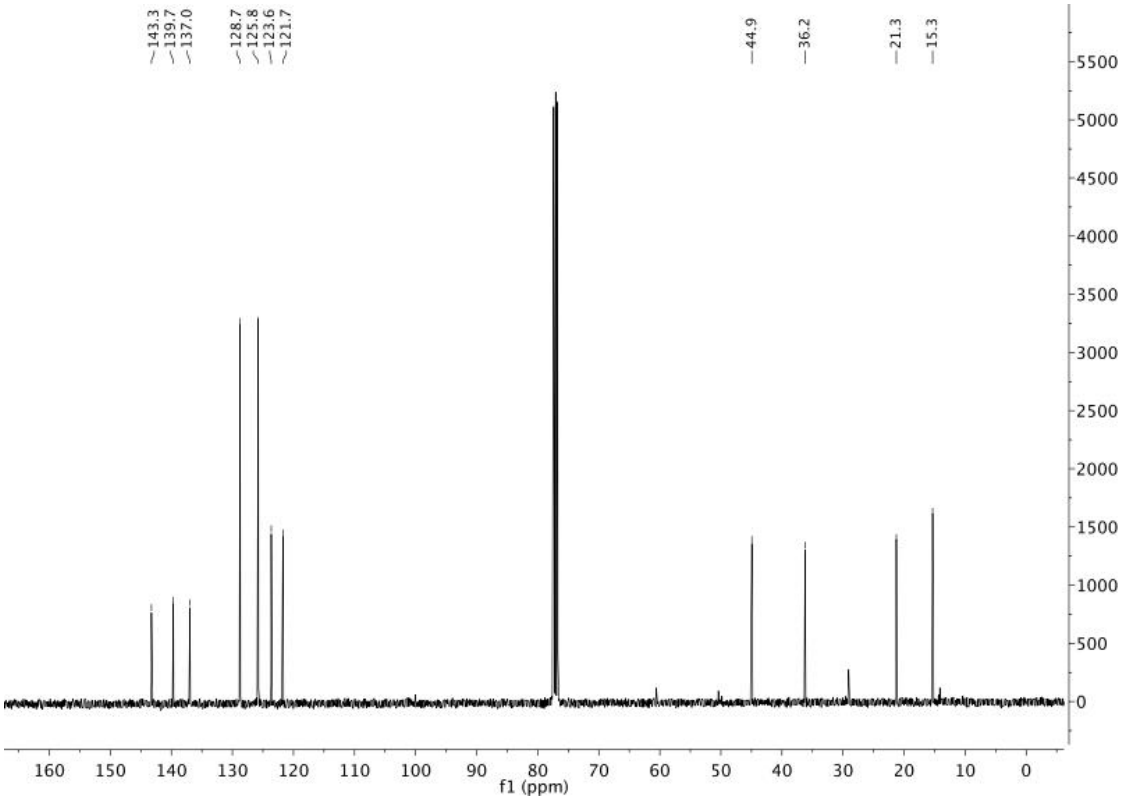

Figure 7.15-^{13}C-NMR spectrum of [Emim]OTs after reaction.

Reaction with [Emim]methoxy ethoxy ethyl sulfate:

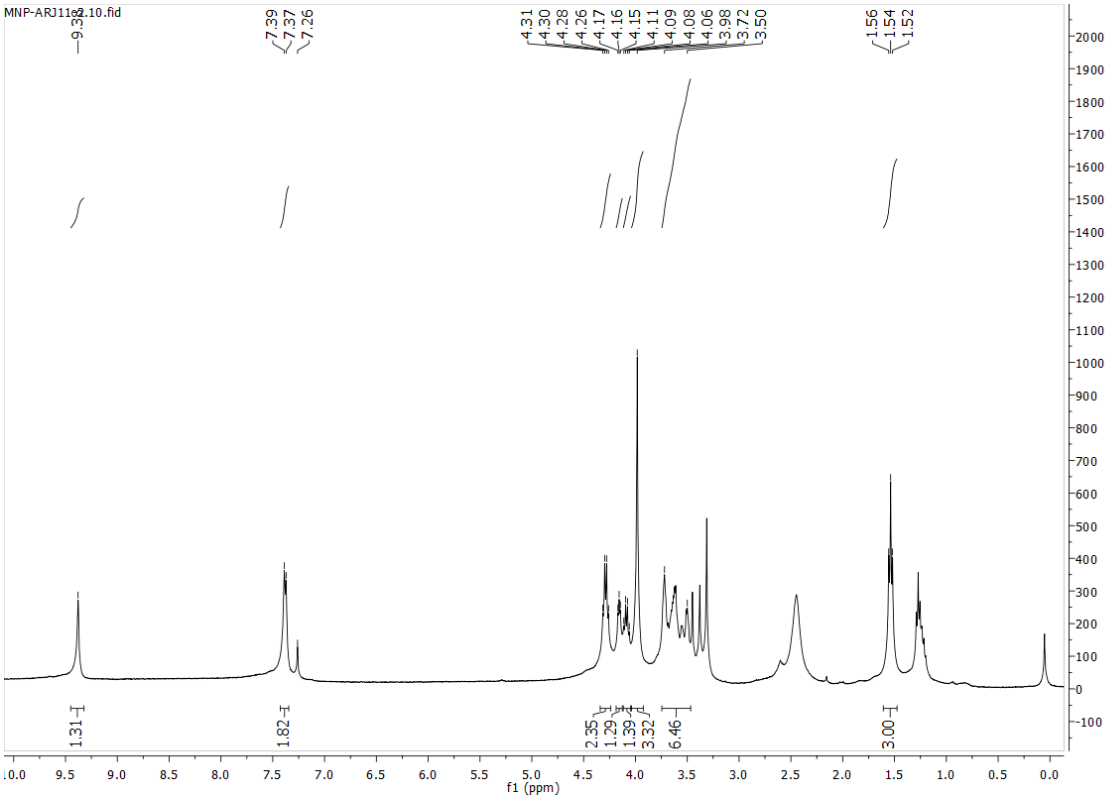

Figure 7.16- ^{1}H-NMR of [Emim]methoxy ethoxy ethyl sulfate after reaction.

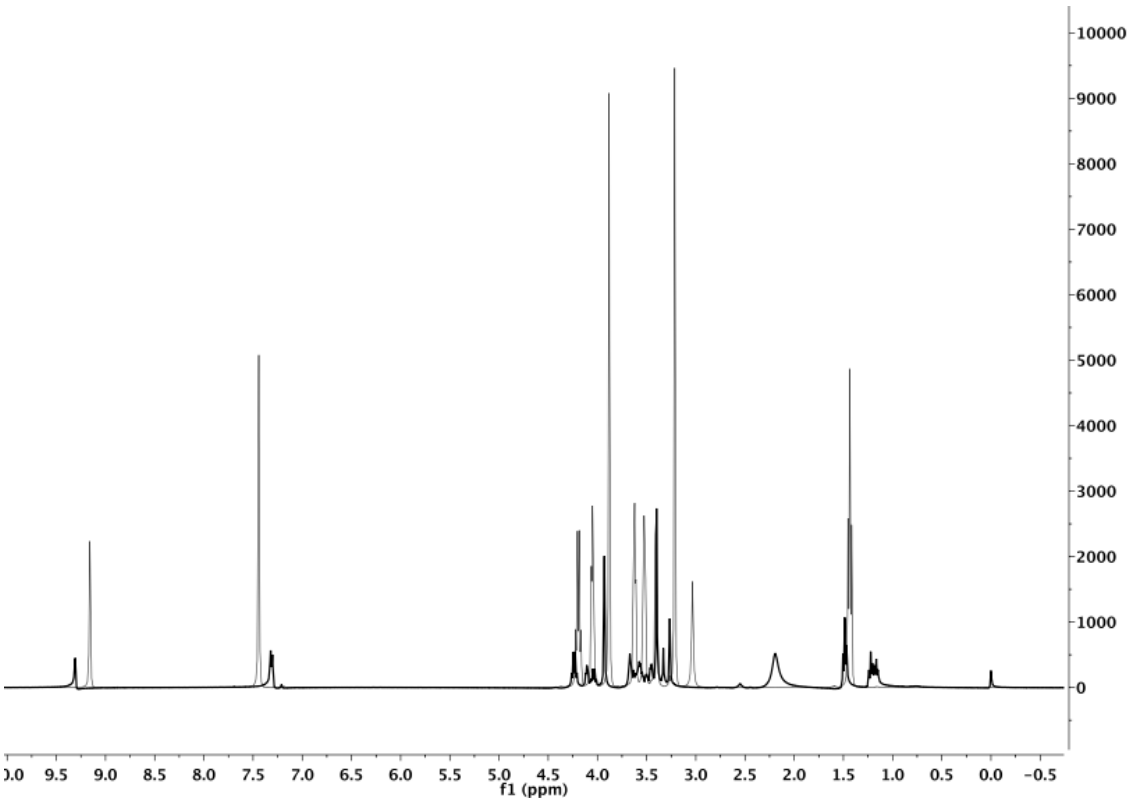

Figure 7.17- Comparison of ^{1}H-NMR of [Emim]methoxy ethoxy ethyl sulfate after reaction with original.

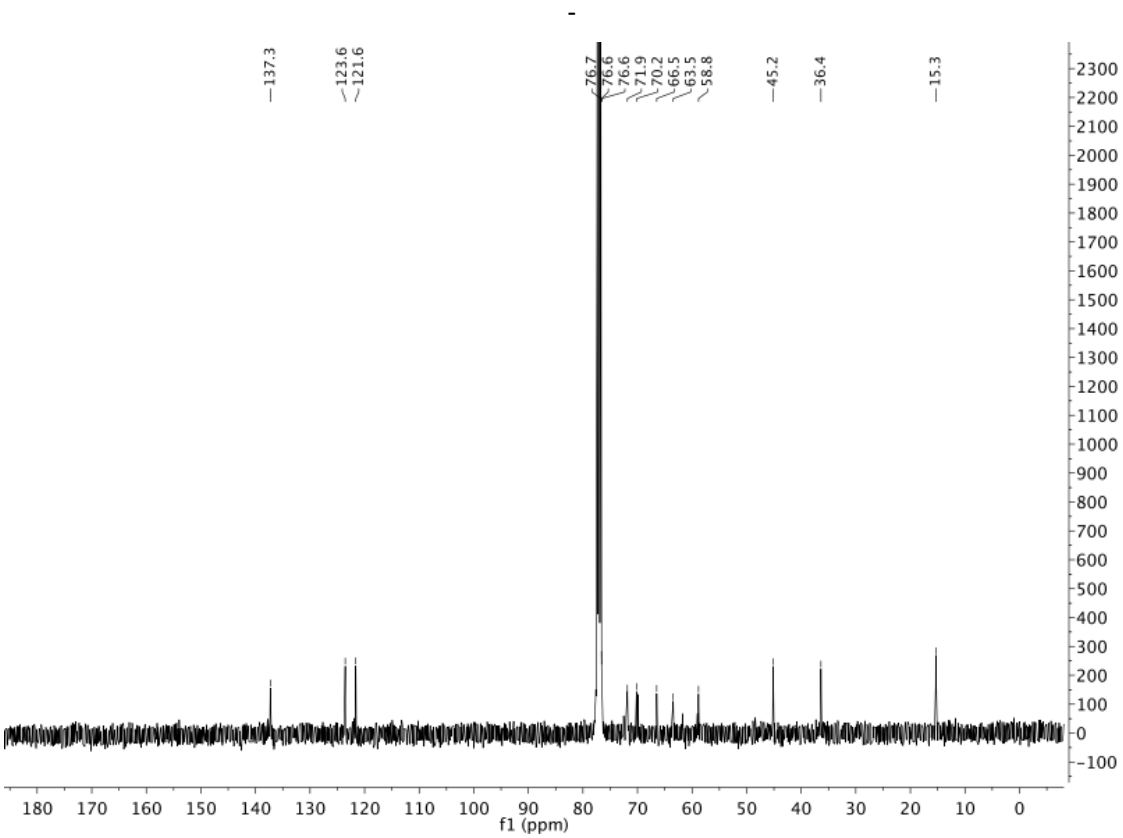

Figure 7.18- ^{13}C-NMR spectrum of [Emim]methoxy ethoxy ethyl sulfate after reaction.

Reaction with [Emim]Cl:

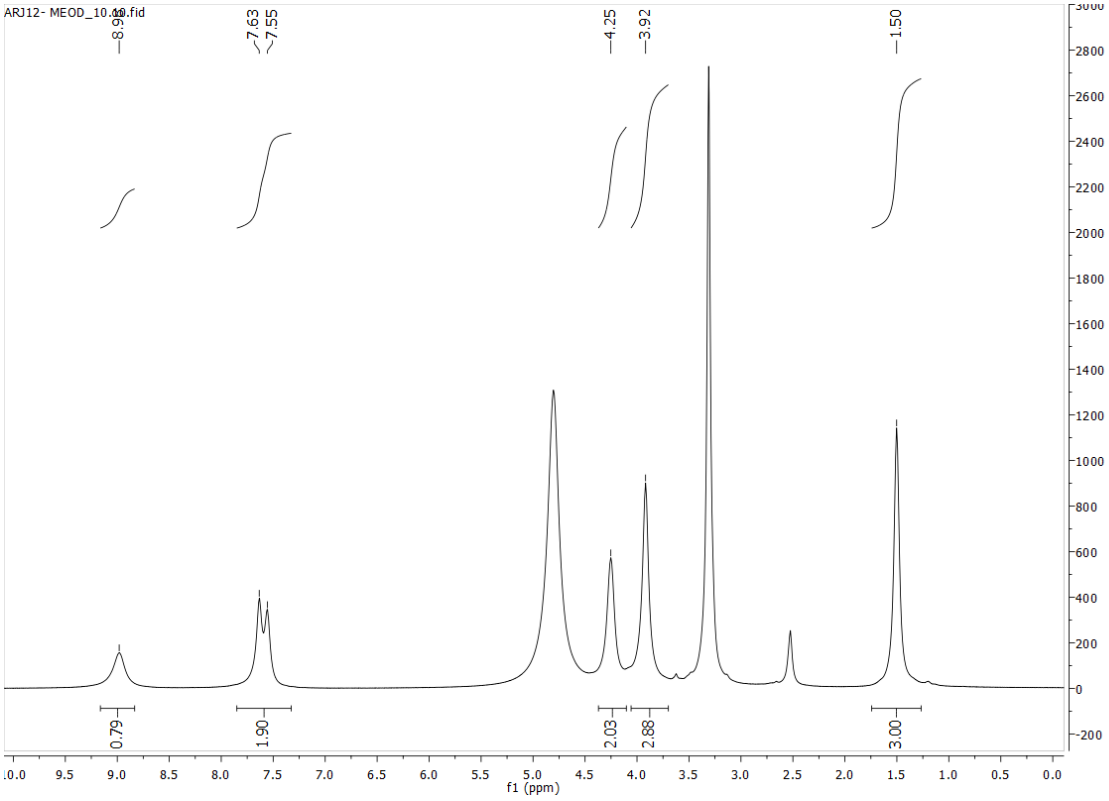

Figure 7.19- ^{1}H-NMR of [Emim]Cl after reaction.

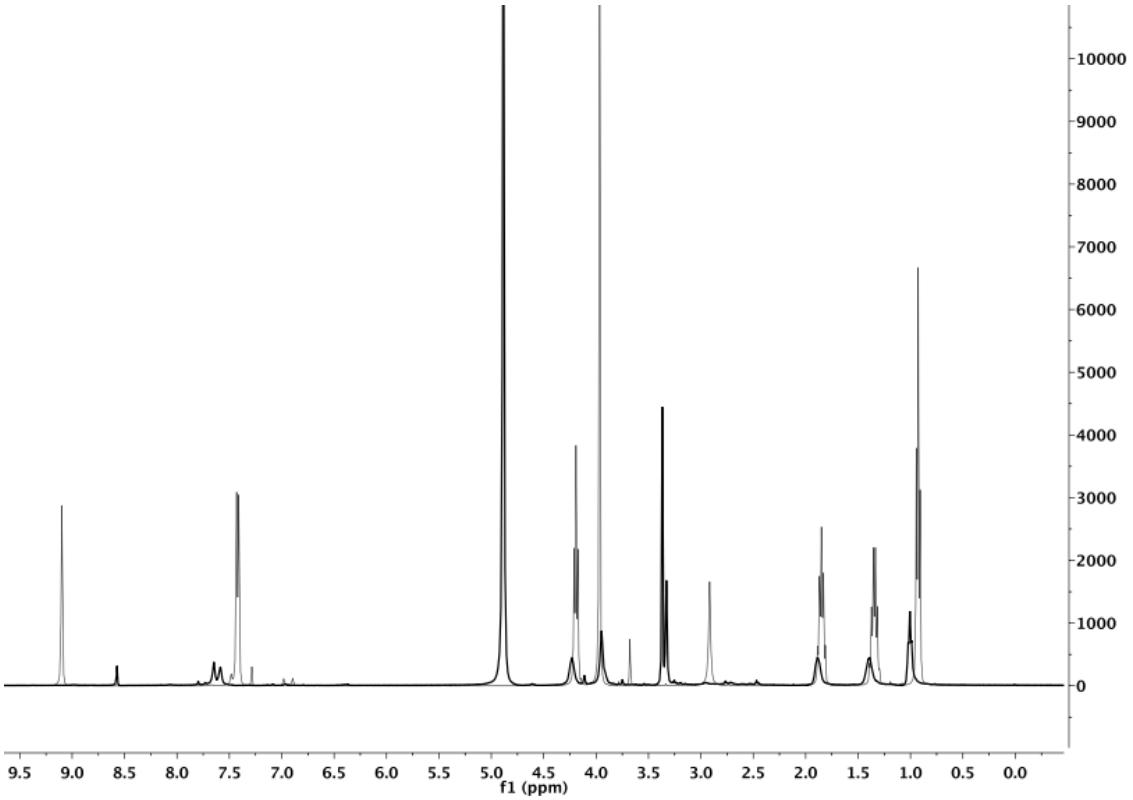

Figure 7.20- Comparison of ^{1}H-NMR of [Emim]Cl after reaction with original.

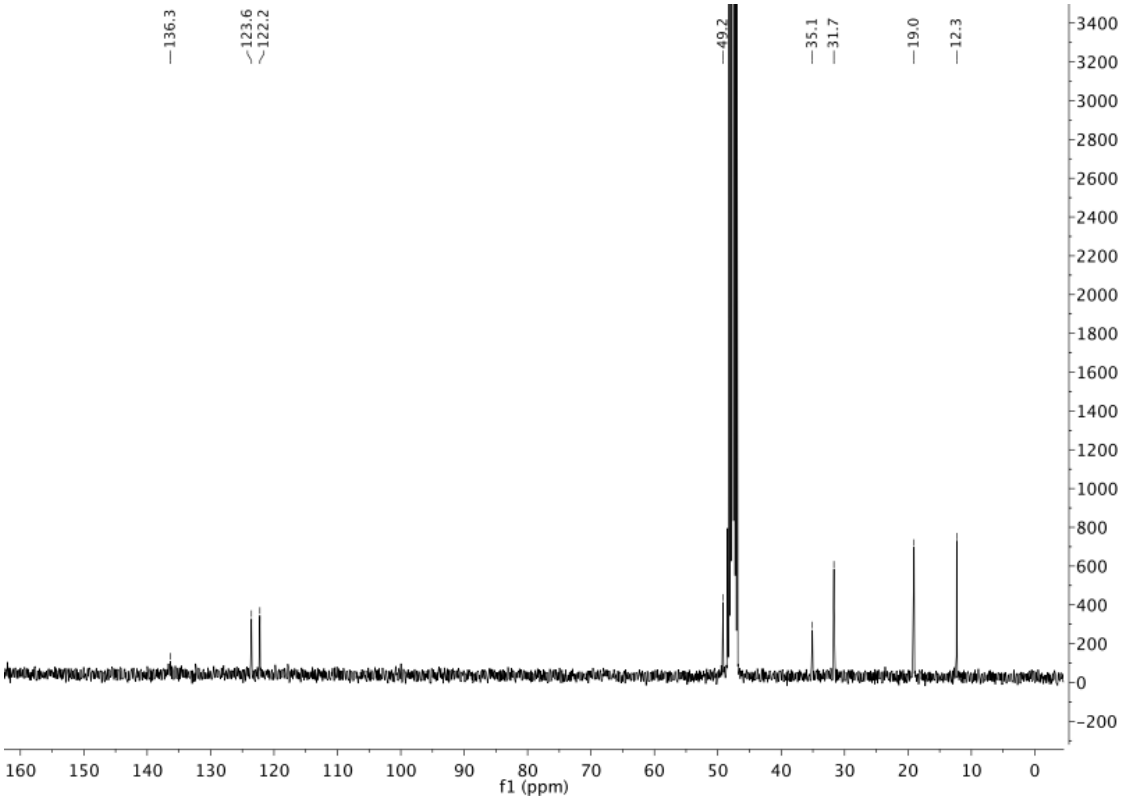

Figure 7.21- ^{13}C-NMR spectrum of [Emim]Cl after reaction.

Reaction with [Emim]Diethyl-phosphate:

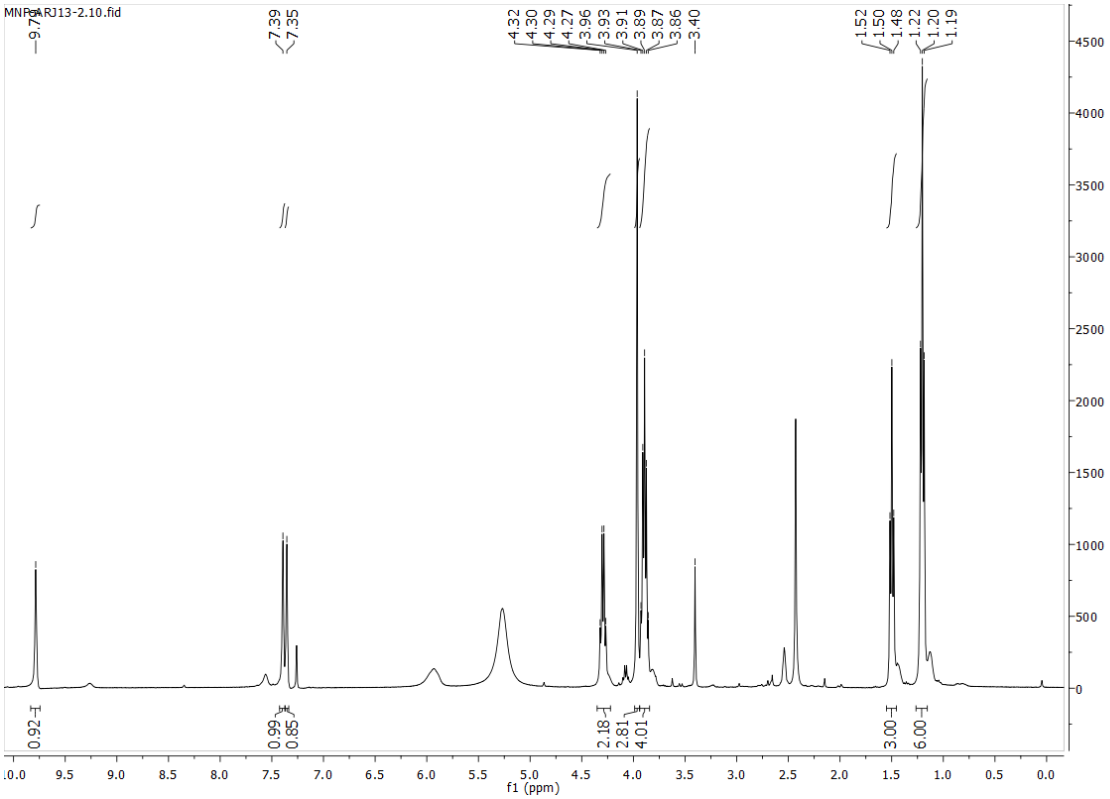

Figure 7.22- ^{1}H-NMR of [Emim]diethyl-phosphate after reaction.

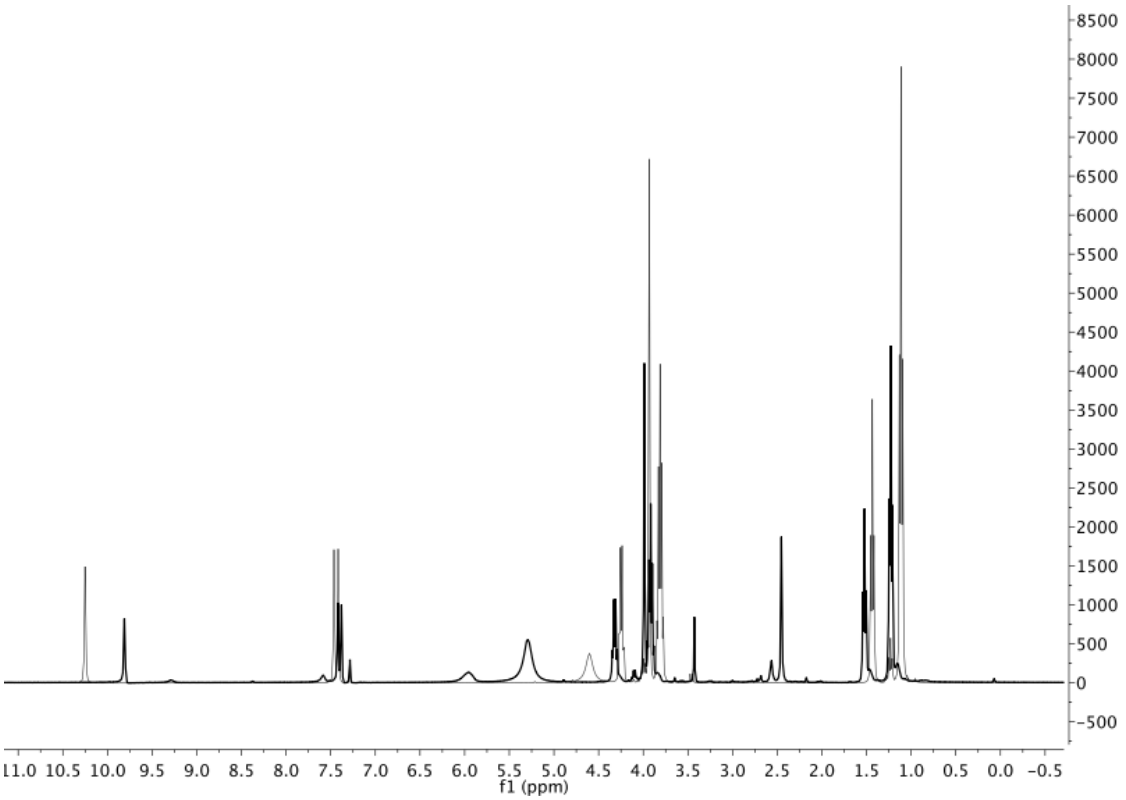

Figure 7.23- Comparison of ^{1}H-NMR of [Emim]diethyl-phosphate after reaction with original.

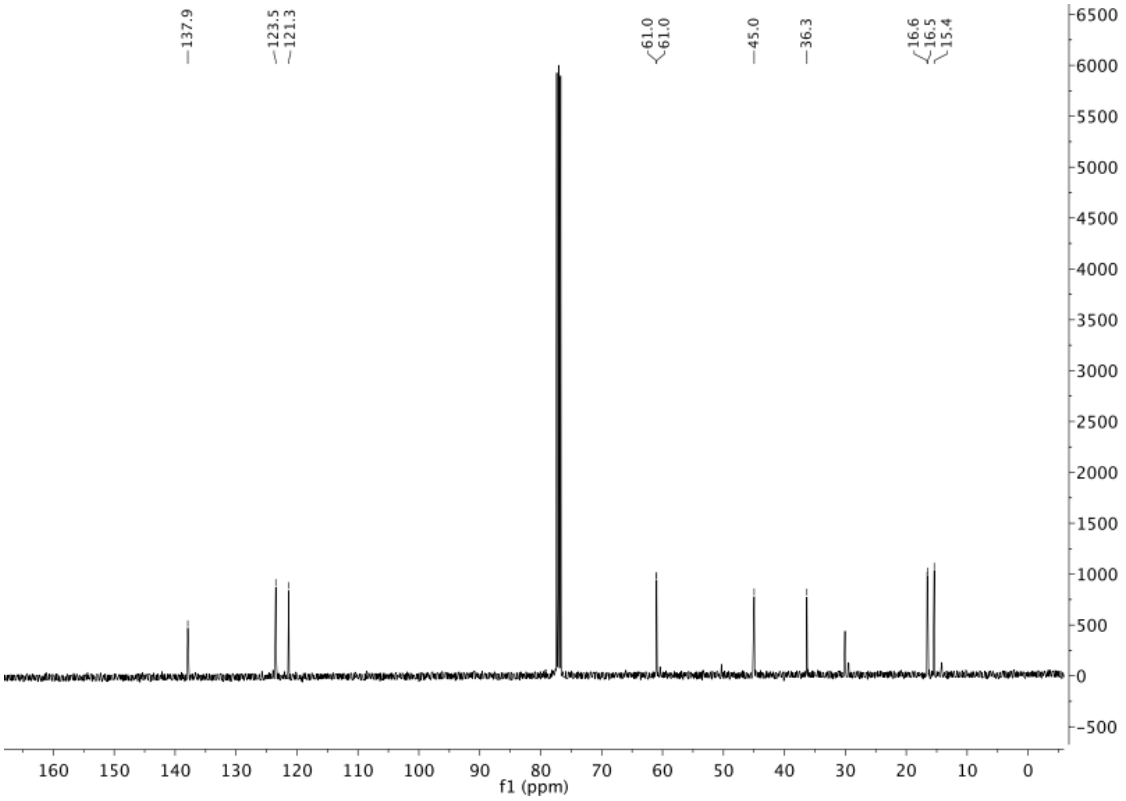

Figure 7.24- ^{13}C-NMR spectrum of [Emim]diethyl-phosphate after reaction.

Reaction with [Emim]DCA:

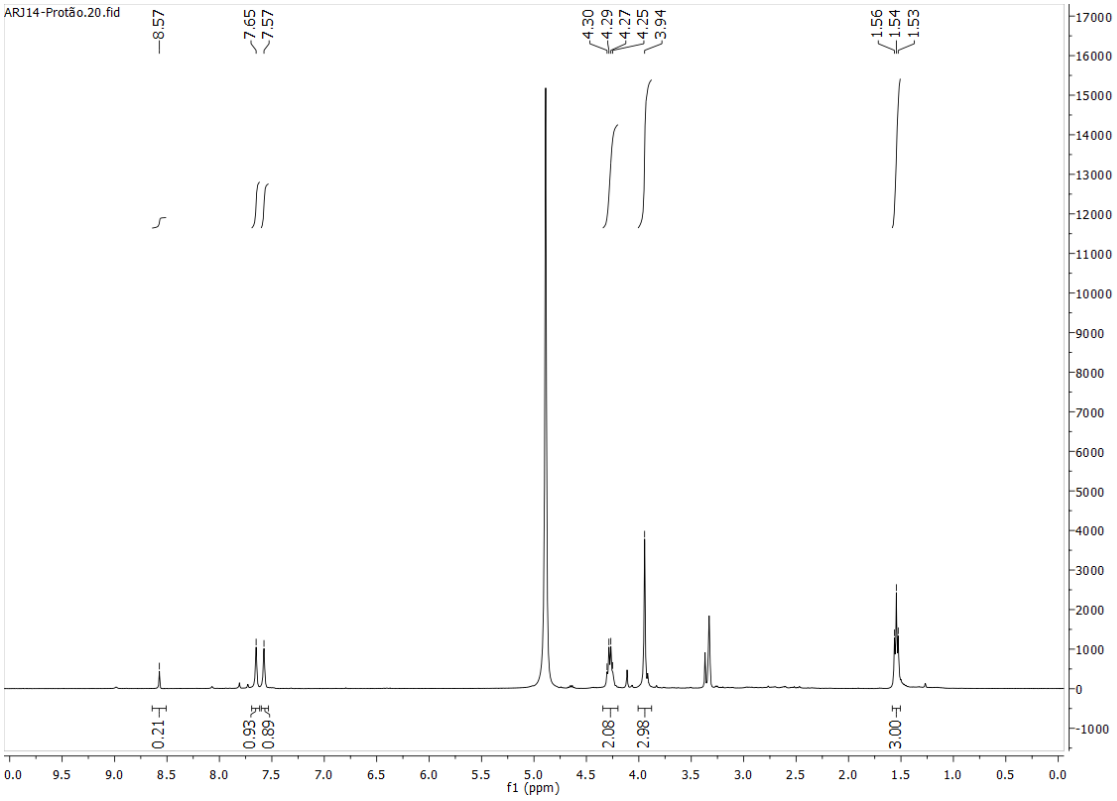

Figure 7.25- ^{1}H-NMR of [Emim]DCA after reaction.

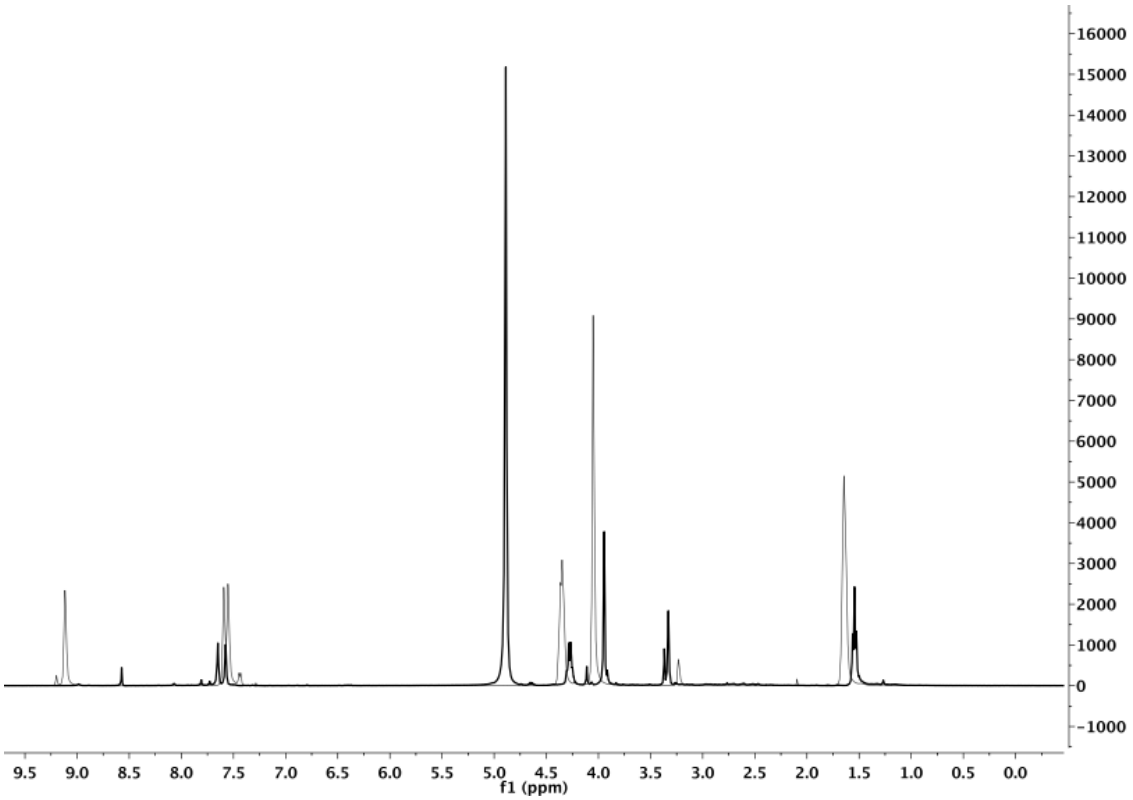

Figure 7.26- Comparison of ^{1}H-NMR of [Emim]DCA after reaction with original.

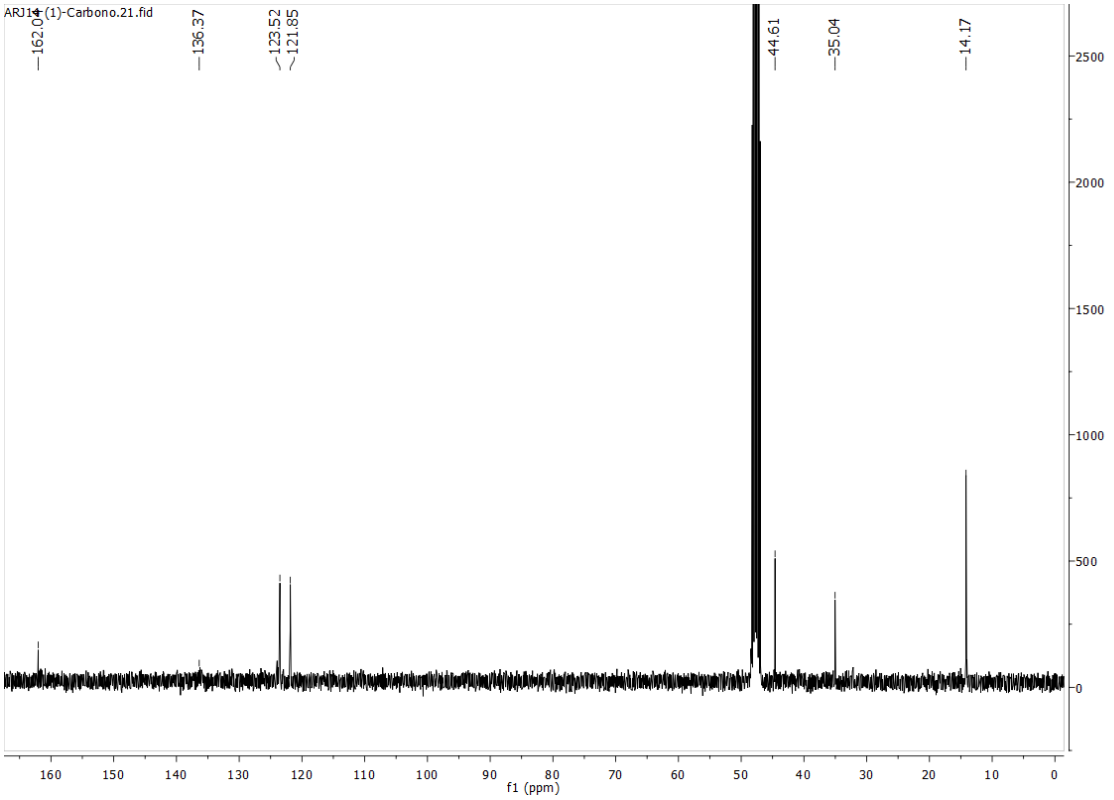

Figure 7.27- ^{13}C-NMR spectrum of [Emim]DCA after reaction.