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CARBON-CARBON BOND FORMING REACTIONS OF BIOMASS DERIVED ALDEHYDES

A Thesis
Presented to
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CARBON-CARBON BOND FORMING REACTIONS OF BIOMASS DERIVED ALDEHYDES

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To those gone before and to those yet to come

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SUMMARY

The objective of this study is to produce α-β unsaturated acids from biomass derived aldehydes via carbon-carbon bond formation (Knoevenagel) reactions. These acids can then be subsequently converted into fuel additives in the gasoline range (C_8-C_9) via hydro-treating. The aldehydes used in this study are 2-furaldehyde (furfural) and 5-hydroxymethyl-2-furaldehyde (HMF). Levulinic acid is also used since it possesses a carbonyl group and has potential as a bio-based starting material.

The Knoevenagel reaction was applied to form a carbon-carbon double bond between the aldehyde and a β di-carbonyl compound. The β di-carbonyl compound used was malonic acid, which can be bio-derived from glucose along fermentation routes. The effects of solvents (THF, water, ethanol, isopropanol, ethyl ether, toluene) and catalysts (e.g. homogeneous and heterogeneous amines, solid basic oxides) on the yields of α-β unsaturated acids were investigated. It was found that the homogeneous amines worked well in THF solvent (90-100% conversion, 99% selectivity for furfural and HMF), while the poly(styrene) supported ethylenediamine gave a higher conversion and selectivity for HMF (65± 5%, 99% selectivity) over furfural (58 ± 7%, 99% selectivity). This trend was also present in competition reactions where both HMF and furfural were reacted in the same vessel. α-β Unsaturated mono-acids for both HMF and furfural were identified as minor side products. However, levulinic acid did not work as well under the conditions studied.

CHAPTER 1

INTRODUCTION

1.1: Motivation for study

Before the industrial revolution, lignocellulosic biomass provided much of humankind's energy requirements [1]. The industrial revolution provided a means for a cheap and abundant supply of fossil fuels to meet humankind's energy requirements, with the three most utilized fuels by industrial economies being oil, coal and natural gas [2]. With the growth of emerging economies and increasing populations (the human population has approximately quadrupled in the 20th century [1]), the continued use of fossil fuels has resulted in an increase in the global demand for energy (primary global energy consumption has increased 16 fold in the 20th century [1]). This energy demand is predicted to increase steadily and a recent study by the National Petroleum Council (NPC) highlights this trend through 2030 [2]. Their projection is shown in Figure 1.

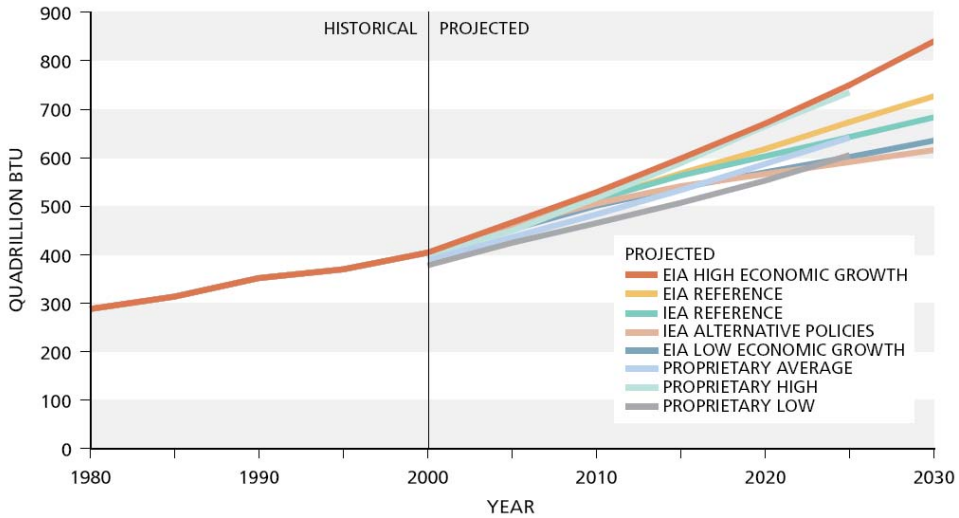


Figure 1: Projected worldwide energy demand through 2030 (From Reference [2], Copyright National Petroleum Council 2007)

To meet this energy demand, several fossil fuel sources (conventional and non-conventional) are being considered. However, worldwide supplies of fossil fuels are projected to grow at a much slower pace than the demand. This is due to uncertainties based on recent difficulties in increasing conventional oil production and the rate and timing at which significant quantities of unconventional resources are utilized [2]. With the increased demand for energy, the supply of energy from conventional sources is projected to be diversified beyond existing capacities. The projection of liquid fuel supply from the NPC study is shown in Figure 2.

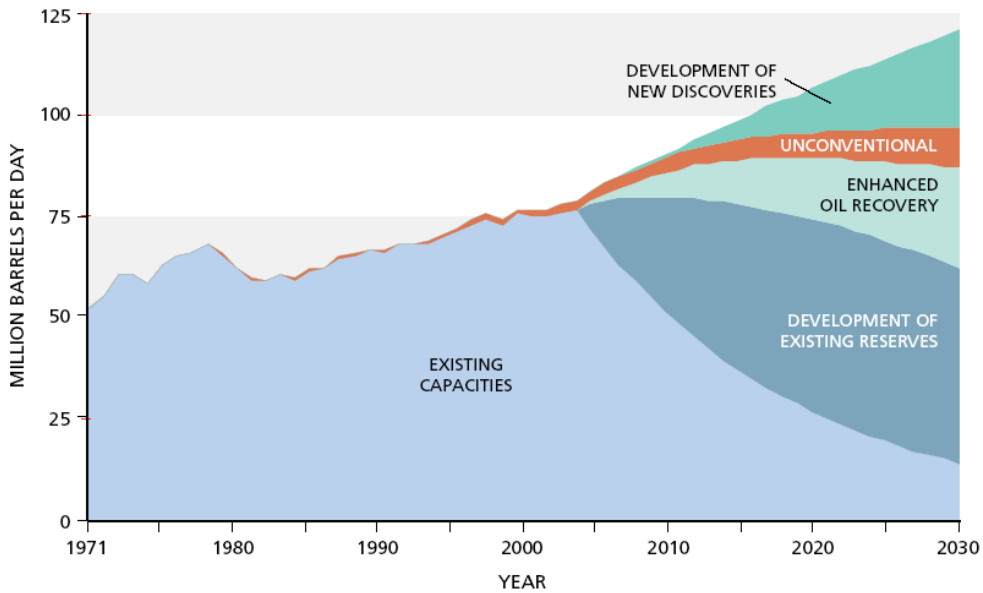


Figure 2: Projected supply of liquid energy sources (From Reference [2], Copyright National Petroleum Council 2007)

Due to these imbalances in the supply-demand equation, the price of West Texas Intermediate (WTI) crude oil has been increasing, and recently crossed 100USD [3]. In addition, levels of atmospheric carbon dioxide (CO_2) are also expected to increase in the future [2]. The projection from the NPC study is shown in Figure 3.

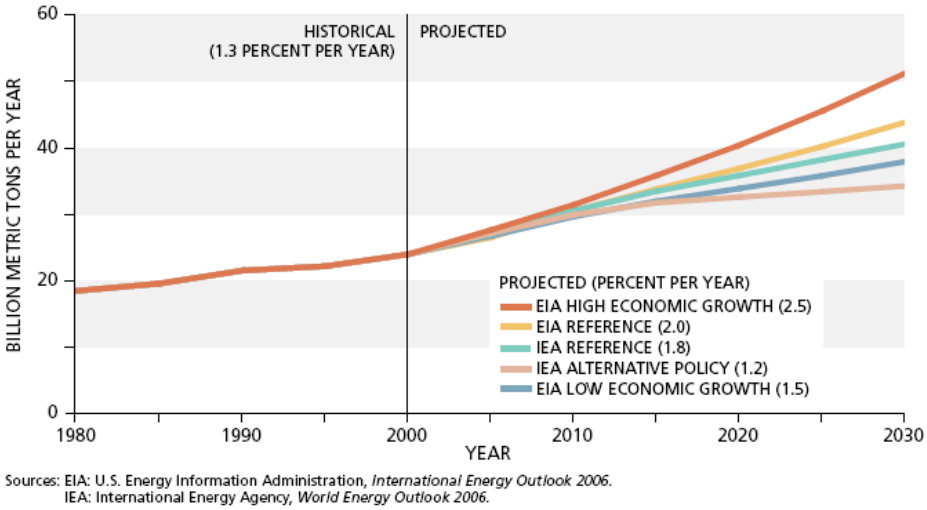


Figure 3: Atmospheric carbon dioxide emission prediction to 2030 (From reference [2], Copyright National Petroleum Council 2007)

With simultaneously increasing energy demand, crude oil cost, and atmospheric CO_2 levels, there is a growing incentive to utilize alternative sources of energy that can meet energy demands in an economical way. Alternative energy sources being considered are solar, wind, geothermal, coal (and coal derived liquids), nuclear, cellullosic biomass fuels, and unconventional petroleum reserves [2]. While there may not be a single approach that can meet all the energy needs of the future, the potential contribution of biomass derived fuels can be significant. In 2003, biomass supplied "nearly 2.3 quadrillion Btu of thermal energy (> 3% of total U.S.A. energy consumption) mainly through industrial heat and steam production by the pulp and paper industry and electrical generation with forestry residues and municipal solid waste" [4]. While this is significant, one question that often arises is the source of available land in the US to grow biomass. A study performed by the U.S. Department of Agriculture (USDA) and Oak Ridge National Laboratory (ORNL) determined that the U.S.A. could potentially produce 1.3 billion dry tons of biomass/year (3.8×10^9 barrel of oil equivalent [5]) through forestland and

agricultural land [4]. The study further stated that the potential biofuels derivable from this amount of dry biomass can "meet more than one-third of the current demand for transportation fuels" [4]. Furthermore, biomass itself can be a renewable feedstock (a portion of the CO_2 evolved from its use is utilized in its production via photosynthesis). Thus, with biomass resources currently available, the development of low-cost technology would aid in the successful utilization of biomass as an energy source. This thesis suggests one such technology: by utilizing carbon-carbon bond formation chemistry, it is possible to produce compounds from biomass which can be used as precursors to fuels.

1.2: Composition and structure of plant biomass

In order to fully utilize plant biomass, it is necessary to understand its composition. Cellulosic (plant) biomass belongs to the classes of hardwoods (Angiospermae) or softwoods (Gymnospermae), which make up the seed-bearing plants (Spermatophytae) [6]. Plant biomass consists of three major groups of polymers: hemicellulose (15-30 wt%), cellulose (40-80 wt%) and lignin (10-25 wt%), with the remaining fraction containing extractives and ash [6].

The hemicellulose fraction contains heteropoly(saccharides) of xylose, glucose, mannose, arabinose and galactose [6]. These are present in pyranose or furanose configurations and some are partially substituted according to the type of hemicellulose (hardwood or softwood) by acetyl groups or glucuronic acid groups (e.g. galactoglucomannans or arabinoglucuronoxylan) [6]. The typical degree of

polymerization is about 200 [6]. Hemiceulluloses are amorphous and are easily hydrolyzed by dilute acids [7].

The cellulose fraction is a highly crystalline linear homopoly(saccharide) with β-1,4 glycosidic linkages of D-glucopyranose monomers [6]. It is the main constituent of wood (40-45 wt%) and is found typically in the secondary cell wall [6]. Due to its high crystallinity, cellulose is not easily hydrolyzed by acid treatment [7].

The lignin fraction contains polymers of coniferyl, sinapyl and coumaryl alcohol structures joined together by phenylpropyl linkages [6]. It gives the plant its strength as it is very resilient to chemical attack. The chair conformation of the pyranose forms (5 carbons) of hemicellulose (galactoglucomannan) and its monomers are shown in Figure 4 along with the cellulose repeat unit and lignin monomers.

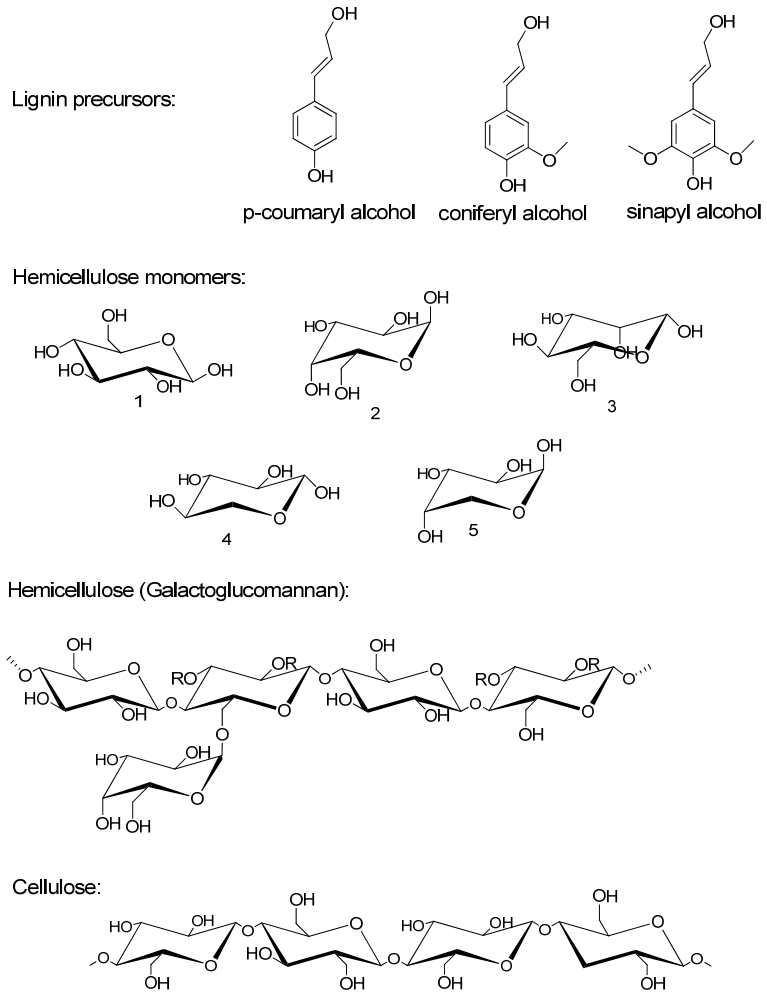


Figure 4: Components in plant biomass: lignin, hemicellulose, and cellulose (Adapted from [6]); 1: β-D-glucopyranose; 2: α-D-galactopyranose; 3: β-D-mannopyranose; 4: β-D-xylopyranose; 5: α-D-arabinopyranose

1.3: Utilization of biomass: Transformation into more useful compounds

Biomass itself can be burnt to produce energy. However, to obtain the maximum use of biomass as a sustainable fuel, the polymeric structures in biomass must first be broken down into simpler compounds. In some cases, these compounds can be used directly as fuels, whereas they often have to be transformed further into liquid fuel species. Typically, this involves an initial pretreatment step which breaks the lignin seal,

opens the biomass structure, and reduces the crystallinity of cellulose [7]. These processes provide an increased accessibility to enzymes or chemicals [8]. Pretreatment is performed via biochemical (enzymatic treatment) [8], thermochemical (chemical treatment) methods [9] or a combination of both [10].

Biochemical treatments allow for greater enzyme digestibility of cellulose, which can be used to produce ethanol. However, lignin and by products of the acidic hydrolysis such as furfural and acetic acid have been identified as inhibitors to enzymatic activity [8]. Avenues to produce cellulosic ethanol along enzymatic routes are confronted with challenges such as high processing costs, large capital investments needed, and a narrow margin between feedstock and product prices [1]. Nonetheless, in the USA ethanol is produced from corn materials and has been approved as an oxygenate (fuel additive) to gasoline in winter months to reduce carbon monoxide emissions [11]. Ethanol is also utilized in E85 fuels (85% denatured ethanol, 15% gasoline) in the U.S.A. [12], while in Brazil ethanol is produced from sugarcane and used directly as a fuel [13].

Among the thermochemical routes, hydrolysis using dilute acid (<5 wt% HCl, TFA, H_3PO_4, HNO_3 [14], [15]) has been applied, with sulfuric acid identified as among the most promising [8]. In this method, the amorphous hemicellulose component is easily hydrolyzed while most of the cellulose remains intact with the lignin being slightly modified [8]. The hydrolytic dissolution process consists of rupture of the glycosidic bonds by the acidic proton and addition of water molecules to separate poly(saccharide) molecules [15]. At times, the dissolution does not affect every glycosidic bond and oligosaccharides are produced instead [15]. Due to the high crystallinity of cellulose, glucose monomers are not easily produced by acid hydrolysis and enzymatic processes

are incorporated with the acid hydrolysis process to produce glucose monomers from cellulose [10]. Other commonly used pretreatments include autohydrolysis [16], and ammonia explosion [17].

Furthermore, biomass can be converted via gasification into syngas (H_2, CO), which can then be converted into alkanes (via Fischer-Tropsch chemistry), alcohols and olefinic compounds [18]. Currently it is more economical, and higher yields are obtained, when hydrogen is produced from natural gas than from biomass [18]. Other processes for the gasification of biomass include pyrolysis (decomposition of organic materials in the absence of oxygen) and partial oxidation [19-21]. In addition, gasification has been conducted in near- and super-critical water [22].

These possibilities can be integrated and utilized in a biorefinery. According to the National Renewable Energy Laboratory (NREL), "a biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass" [23]. The refinery would operate in a similar fashion to current petroleum refineries, which convert crude oil to fuels and fine chemicals [5]. The driver of the biorefinery would be the different functionalities present in biomass, allowing for the production of "several low-volume, but high-value, chemical products and a low-value, but high-volume liquid transportation fuel, while generating electricity and process heat for its own use" [23]. However, several challenges exist that must be overcome before the biorefinery concept becomes a reality [24]. These challenges include separation and purification of products, processing and pretreatment technologies[10], as well as overcoming the heterogeneity of biomass species produced in different locations. In addition, the competition for the use of land to grow crops versus the use of land to

grow biofuels would have to be addressed. Nonetheless, the biorefinery option would be viable as long as the economics are favorable for the production of biomass derived fuels compared to the overall cost of fossil fuels production.

1.3-1: Further utilization of biomass: Production of furfural, HMF and levulinic acid

Biomass derived molecules usually contain many functional groups and have large oxygen contents. In order to produce a fuel from a biomass-derived compound, its oxygen content must be reduced to increase its stability and energy density [5]. It has been approximated that biomass contains typically 40-45 wt% oxygen [5]. Three of the many oxygenated compounds that have potential for conversion into fuel compounds are furfural, HMF and levulinic acid [25]. Their structures are shown in Figure 5.

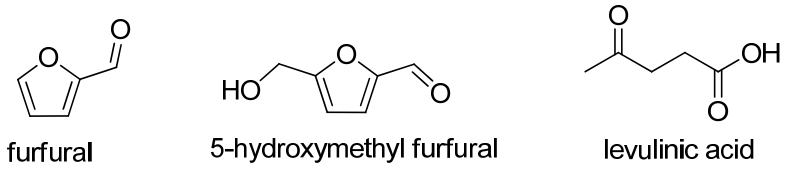


Figure 5: furfural, HMF and levulinic acid

<u>Furfural</u>

The first commercial process for furfural production was implemented by the Quaker Oat Company. Starting from oat husks as raw materials, they obtained yields around 40-50% [26]. Furfural is used as an industrial solvent in the refining of lubricating oils and as a resin [26], and approximately 70% of the global furfural production capacity is located in China [27]. In 2002, the worldwide production of furfural was estimated to be $3x10^5$ Mt, with a market price around \$1700 t^{-1} [28]. In the presence of dilute acids at high temperatures, pentoses (C_5 monosaccharides) can be dehydrated to form 2-furaldehyde (furfural) [29]. Antal and co-workers working with the acid catalyzed

dehydration of D-xylose showed that in addition to furfural, other dehydration, isomerization and condensation products were formed [29].

HMF

A route to the production of HMF from furfural via hydroxymethylation using formaldehyde has recently been reported [30]. HMF has applications for the synthesis of glycols, ethers, polymers and pharmaceuticals [31], but there is currently no large scale production process for HMF. In acidic media, the Hexoses (6 carbon sugars) are dehydrated to form 5-hydroxymethyl-2-furaldehyde (HMF). Starting with D-fructose, Antal and co-workers provided evidence which supports their proposed mechanism [32].

Other researchers have also started with sucrose and inulin to obtain HMF [33]. While glucose is the most abundant C_6 monosaccharide, the dehydration of glucose to HMF without pretreatment is not as favorable as the dehydration of its isomer fructose [34]. After treatment of the aqueous glucose solution with potassium hydroxide and reaction with 0.25% oxalic acid, HMF was liberated [34]. In non-aqueous solvents such as dimethyl sulfoxide (DMSO) and 1-methyl-2-pyrrolidinone, the conversion of fructose to HMF is favored, and selectivities of 90% and higher have been achieved [35].

Levulinic acid

It is estimated that the Biofine process by BioMetics could produce 1000-2000 dry tons/day of levulinic acid in 50-70% yield using a large scale pilot plant [5]. The targeted selling price is around $0.09-$0.11/kg [5]. Chemically, HMF can be hydrolyzed to further produce levulinic acid (4-oxopentanoic acid) and formic acid in a 1:1 ratio under acidic conditions [36]. Using ^{13}C NMR spectroscopy, Horvat and co-workers were

able to deduce a mechanism for the production of levulinic acid from HMF [36]. The overall reaction is shown in Figure 6.

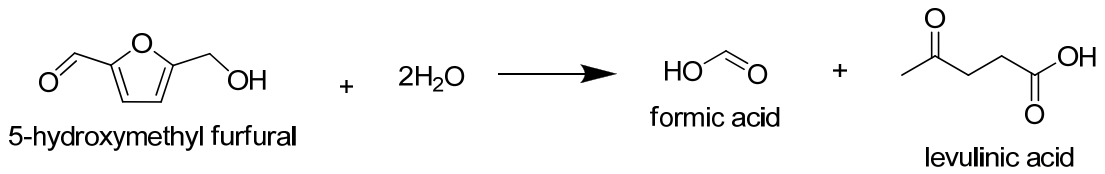


Figure 6: Formation of levulinic and formic acids from HMF [36]

Figure 7 shows the different equilibrium structures that levulinic acid can form. Under normal conditions, levulinic acid exists in equilibrium between the open and lactone forms (Species **3**) as shown in Figure 7. This is attributed to an intermolecular transfer of the proton from the carboxylic acid group to the carbonyl group, forming 5-hydroxy-γ-valerolactone (Species **3**) [37]. In acidic media, the concentrations of species **1** and **2** are greater than in neutral conditions, and these species can undergo dehydration to form the lactones **4** and **5** (See Figure 7) [37].

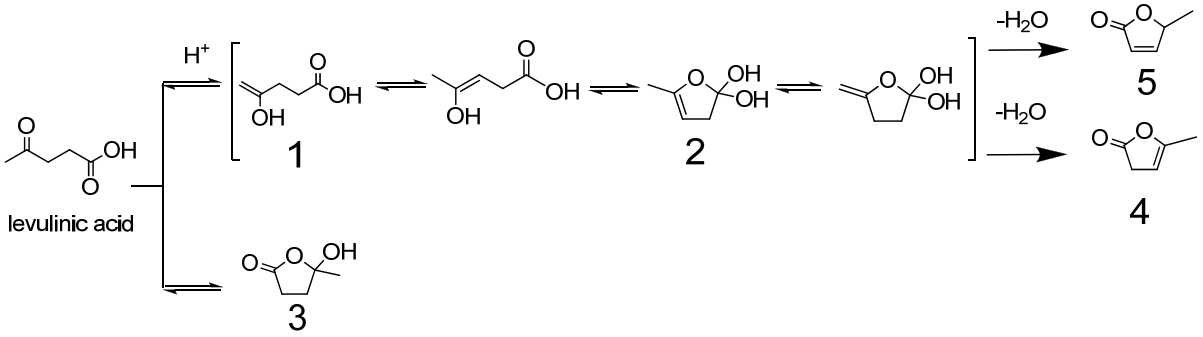


Figure 7: Equilibration structures of levulinic acid under acidic and normal conditions (Adapted from Reference [37])

1.3-2: Utilization of biomass compounds: Aldol condensation for alkane production

Once the biomass is accessible to chemicals or enzymes, several options exist to utilize the fractions produced. For instance, lignin can provide avenues to fuels via base-catalyzed depolymerization followed by hydroprocessing [38]. One problem in using the

sugar fraction is that when the cellulosic polymers are broken down, the fragments are generally of size C_6 and smaller. However, for gasoline and Diesel fuels, chains C_8 and higher are needed. Thus, a key need are technologies that can be used to produce hydrocarbons or mildly oxygenated hydrocarbons that are C_8 and larger from biomass. In this thesis, we develop a strategy to link biomass derived compounds (which have a lower heating value e.g. HMF and malonic acid) via carbon-carbon bond formation chemistry to obtain compounds of desired molecular weights and composition (e.g. C_8-C_9 alkanes for gasoline). Before describing the new process, we first review the one key example in the literature that serves as a precedent.

In an effort to develop new routes to produce liquid alkanes from biomass derived compounds, Dumesic and co-workers developed a method for the production of hydrogen, methane and higher alkanes via aqueous phase reforming of biomass model compounds, e.g., sorbitol, ethylene glycol, glucose and glycerol [39, 40]. They also conducted further research on sequential aldol condensation of biomass derived compounds (acetone, furfural and HMF) [41].

Starting with several polysaccharides (e.g. xylose, inulin, sucrose), they utilized acid-catalyzed reactions to form furfural and HMF, which were then reacted over a bi-functional solid base catalyst ($Pd/MgO\text{-}ZrO_2$) via the aldol condensation [25, 42]. These compounds were subsequently hydrogenated over Pd/Al_2O_3 to produce water soluble compounds (See Figure 8) [41]. Once formed, these water soluble compounds were subsequently converted to alkanes via aqueous phase dehydration/hydrogenation reactions in organic and inorganic feed streams over a Pt catalyst containing acid and

metal sites [25, 41]. An example is shown in Figure 8 starting from two molecules of furfural and 1 molecule of acetone [25].

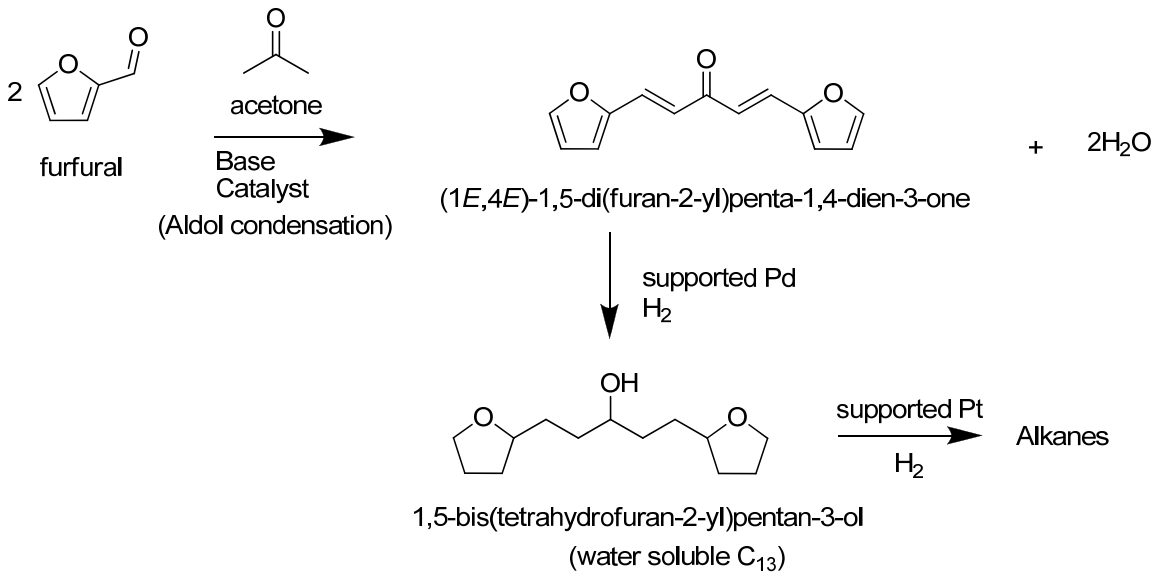


Figure 8: Overall process utilizing the Aldol condensation to produce alkanes starting from furfural and acetone (Adapted from Reference [25])

While the mechanism of the aldol reaction is similar to the Knoevenagel condensation in terms of the steps involved (e.g. enolate ion formation), this study extends to the carbon-carbon bond formation capability of furans by utilizing methylene compounds for the production of fuels. Whereas the previous method of Dumesic utilized acetone, a chemical derived from oil to extend the chain of furan compounds, we report here the use of malonic acid, a species that can be derived from glucose, to extend the chain and give gasoline range molecules that are wholly derived from biomass.

1.3-3: Utilization of furfural, HMF and levulinic acid via the Knoevenagel reaction for the production of fuels

As each of the reactants furfural, HMF and levulinic acid possesses a carbonyl group (-C=O), the Knoevenagel reaction (which requires an aldehyde/ketone, an

activated methylene compound, and a base as catalyst), can be used to form a carbon-carbon double bond between the aldehyde/ketone and an activated methylene compound. An activated methylene compound contains a $-CH_2-$ group between two electron withdrawing groups (EWG), e.g. carboxylic acid, ester, nitrile. The presence of the EWG facilitates hydrogen abstraction from the methylene by a base so that the methylene species can react with the aldehyde to form an unsaturated compound and water. Once hydrogenated, the unsaturated compounds would be in the gasoline range (C_8-C_9).

There are two proposed mechanisms for the Knoevenagel reaction when catalyzed by amines. The mechanism described below for furfural and malonic acid is due to Hann and Lapworth, and is shown in Figure 9 [43]. The reaction proceeds following in three stages:

1. The catalyst forms an enolate ion (nucleophile) by removing one of the protons from the methylene group ($-CH_2-$ group of malonic acid in Figure 9). The resulting species is resonance stabilized.
2. The enolate ion attacks the carbonyl group, forming a carbon-carbon bond.
3. The molecule loses a water molecule via an aldol-type condensation to form an unsaturated di-acid.

There is also a side reaction that produces an unsaturated (carbon-carbon double bond) mono-acid via evolution of carbon dioxide from the primary product (decarboxylation). The position of the unsaturation depends on the aldehyde/ketone used and has been identified in the α-β position or in the β-γ position to the carboxylic acid group [44]. The mechanisms for the decarboxylation reactions are described in the literature [44].

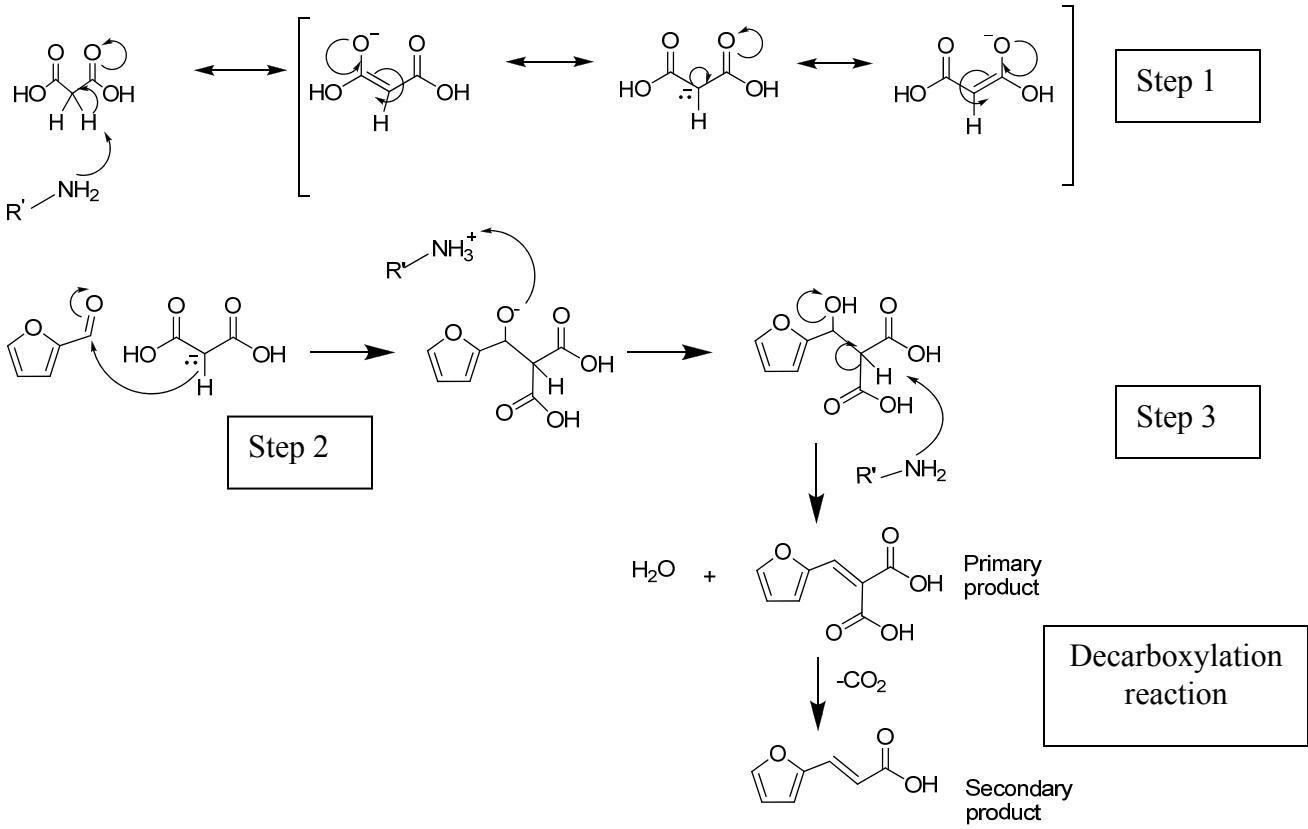


Figure 9: Mechanism of the Knoevenagel Reaction between furfural and malonic acid [43]

The activated methylene compound of interest is malonic acid as it can be bio-derived from glycerol or glucose along enzymatic routes [45]. The glycerol (or glucose) is converted to 3-hydroxypropionicaldehyde which can then converted to 3-hydroxypropionic acid (3HPA) [45]. This can be subsequently oxidized to malonic acid. Malonic acid and its esters are used in the production of vitamin B1 and B6, pharmaceuticals, agrochemicals, and flavor compounds [46]. In a study performed by NREL to determine the 30 platform molecules derived from sugars which have the highest potential for use in a biorefinery, 3HPA was included [47]. According to a recent review [46], and several patents, it was reported that 3HPA was oxidized to malonic acid using oxygen with Pt/C with yields higher than 90% [48, 49].

The product of the Knoevenagel condensation with HMF and malonic anid is an unsaturated C_9 compound which has an IUPAC name of 2-((5-hydroxymethyl)furan-2-ylmethylene) malonic acid. The same reaction starting from furfural produces an unsaturated C_8 compound 2-(furan-2-ylmethyelene)malonic acid. Starting with levulinic acid, the compound formed is 2-methylbut-1-ene-1,1,4 tricarboxylic acid. These acids can then be hydrogenated to produce alkanes. Typically, acid groups are removed via hydrodeoxygenation using supported sulfided bi-metallic catalysts (e.g. Co/Mo) [50], or over a supported noble metal catalyst (e.g. Ru/C) [51]. The overall process including the Knoevenagel reaction and hydrogenation is summarized in Figure 10.

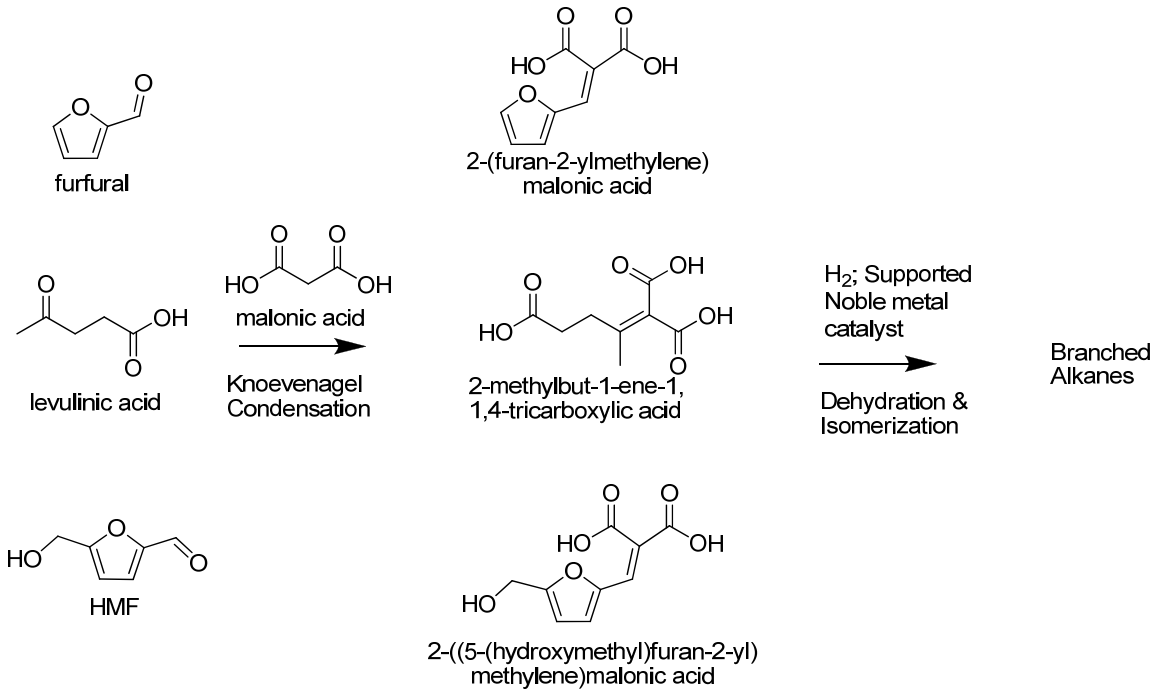


Figure 10: Paths to alkanes via the Knoevenagel reaction of bio-derived dehydration compounds

1.4: Research Objectives

This thesis reports an investigation of the effect of the following variables on the Knoevenagel reaction of malonic acid with furfural, HMF and levulinic acid:

a. Catalyst

b. Solvent

c. Concentration

d. Competition reactions

Also, preliminary hydrogenation of 2-((5-hydroxymethyl)furan-2-ylmethylene)malonic acid was performed using 5 wt% Ru/Al_2O_3, and the ^1H NMR results are presented.

CHAPTER 2

STATE OF THE ART OF THE KNOEVENAGEL REACTION

2.1: The Knoevenagel Condensation reaction

The Knoevenagel Condensation reaction is named after Emil Knoevenagel [52], who in 1896 identified the reactions of aldehydes and ketones that undergo carbon-carbon bond forming reactions with an activated methylene compound ($X\text{-}CH_2\text{-}Y$, where X and Y are electron withdrawing groups (EWG)) to produce an α,β-unsaturated compound. The mechanism was described in Section 1.3-3 (page 14). The general reaction is shown in Figure 11.

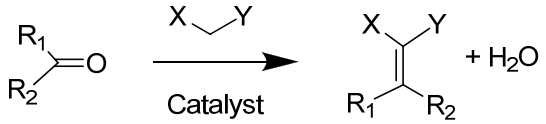


Figure 11: General Knoevenagel reaction [53]
R_1 and R_2 can be H or any other substituent group; X and Y are electron withdrawing groups.

Among the EWG used as X and Y in Figure 11 are NO_2, quaternary pyridinium or similar heterocycles, CN, COR (and COAr), CONHR (and CONHAr), CO_2R, CO_2H, SO_2, S, Ar (and ortho, meta, para EWG), pyridine and similar electron deficient heterocycles [53]. With respect to positions R_1 and R_2, virtually every aldehyde has been shown to undergo the reaction in the literature, with ketones being less reactive [53]. As a result, the reaction is frequently used as a test reaction in organic synthesis chemistry to characterize the base activity of catalysts (e.g. [54-57]) and there is a very extensive literature on the reaction [53].

2.2: Catalysts used in the Knoevenagel Condensation reaction

While not exhaustive, Table 1 lists some catalysts that have been used in the literature for the Knoevenagel reaction.

Table 1: Catalysts that have been used for the Knoevenagel reaction

Catalyst	Reference
Amines (primary and secondary)	[54-57]
glycine	[58]
Tertiary amines (Pyridine & β-alanine: Verely-Doebner modification)	[59, 60]
Diammonium hydrogen phosphate	[61]
12-tungstenophosphoric acid	[62]
Lewis acids (e.g. LiBr)	[63]
Zeolites (e.g. rare-earth exchanged NaY zeolite)	[64]
Hydrotalcites (layered double hydroxides)	[55]
Salts (e.g. acetamide, ethylenediamine acetate, ammonium acetate, triethylamine acetate)	[43]
Ionic liquids (e.g. 1-butyl-3-methylimidazolium hydroxide)	[65]

In addition, several authors have performed the reaction without a solvent [63], and without a catalyst using microwave radiation [66]-[67]. In addition to homogeneous catalysts, supported catalysts have also been utilized successfully [54, 57].

2.3: The Knoevenagel reaction of furfural, HMF and levulinic acid with malonic acid

This section summarizes the available literature on the Knoevenagel reaction between malonic acid and each of furfural, HMF and levulinic acid.

Furfural

Table 2: Catalysts and conditions used in Knoevenagel reaction of furfural and malonic acid

Catalyst	Special reaction conditions	Reference
Alumina	Microwave irradiation	[66]
K_2CO_3; Na_2CO_3; $KHCO_3$; KOH		[68]
bentonite	Microwave irradiation	[67]
Alumina	Ultrasound radiation	[69]
Zeolites		[70]
Unknown.	^{1}H and ^{13}C NMR study	[71]
KOH	Base hydrolysis of the di ethyl ester in Ethanol	[72]
Aniline	Produces Furfuralmalonic acid	[73]
Alcoholic ammonia		[74]
n-Amylamine		[75]
Piperidine & pyridine		[76],[77]

HMF

Table 3: Catalysts and conditions used in Knoevenagel reaction of HMF and malonic acid

Catalyst	Special feature	Reference
Diethylamine		[78]
	Decarboxylation of 2-((5-hydroxymethyl)furan-2-ylmethylene)malonic acid	[79]

Levulinic acid

Table 4: Catalysts and conditions used in Knoevenagel reaction of levulinic acid and malonic acid

Catalyst	**Solvent**	**Special feature**	**Reference**
Ammonium acetate	Benzene, glacial acetic acid	Heated overnight under reflux using a Dean-Stark trap	[80]

While there is much literature on the Knoevenagel reaction of furfural and malonic acid, there are fewer papers that describe experiments starting with HMF (or levulinic acid) and malonic acid. Furthermore, the papers do not utilize the formed compounds for the production of fuels except Reference [80]. This thesis is therefore motivated to fill the literature and to convert the compounds produced into fuels or fuel additives.

CHAPTER 3

EXPERIMENTAL

3.1: Reagent grade and source of chemicals

The following chemicals listed in Table 5 were utilized in this study without further purification.

Table 5: Reagent grade and source of chemicals used in study

Chemical	Reagent type	Source
2-Furaldehyde (furfural)	99% A.C.S. reagent	Sigma-Aldrich
5-(Hydroxymethyl)furfural	99%	Sigma-Aldrich
4-Oxopentanoic acid (Levulinic acid)	≥ 98.0%	TCI America
Malonic acid	99%	Sigma-Aldrich
Malononitrile	99%	ACROS
n-Dodecane	Not given	TCI America
Tetrahydrofuran (THF)	≥ 99.0% A.C.S. reagent, contains 250ppm BHT as stabilizer	Sigma-Aldrich
Isopropyl alcohol (isopropanol)	99.5%	VWR
Ethyl ether	Anhydrous, A.C.S. grade	EMD
Ethyl alcohol (Ethanol)	Absolute, 20 proof, 99.5% A.C.S. reagent	ACROS
Ethyl acetate	99.5%	VWR
N-propylethylenediamine	99%	ACROS
Ethylenediamine	99%	Sigma-Aldrich

3.1-1: Properties of reactants

Table 6 lists the physical properties of the aldehydes (furfural, HMF), ketone (levulinic acid) and the activated methylene compound (malonic acid) used.

Table 6: Physical properties of reactants

Chemical	**Boiling point /°C [81], [82]**	**Melting point /°C [81], [82]**	**Solubility in 100 parts water [81]**
furfural	161.7	-38.7	9.1 (13°C)
HMF	114-116 (1mmHg)	28-34	Soluble
levulinic acid	245-6	33.5	Very Soluble
malonic acid	Decomposes	130-5	138 (16°C)

3.2: Solvents used in this study

The solvents used in this study and their physical and chemical properties are given in Table 7. They were chosen based on type (protic, non protic, ethers, and esters), boiling points, dipole moments and dielectric constants. Also, the solubility of water in the solvent is important since water is a product of the Knoevenagel reaction. Although alcohols tend to form hemi-acetals in reactions with aldehydes, they were chosen since several researchers have noted improved conversion with the addition of alcohol to the reactions with amine catalysts. Ethers were chosen as they have been used in the literature for the reaction. In particular some of these solvents can be dangerous (e.g. ethyl ether can form peroxides on storage), while some are environmentally benign (e.g. water). The ideal solvent would not react with the species present in solution and would be easily recoverable in high purity at the end of the reaction. Table 7 lists several properties of the solvents used in this study.

Table 7: Physical and Chemical properties of solvents used in this study

Solvent	Boiling point /°C [81]	Dipole moment (D) [82]	Dielectric constant [82]	Solubility in 100 parts water [81]
THF	65-66	1.8	7.5	Soluble
Water	100	1.85	80.1	∞
Ethyl acetate	77.1	1.78	6.1	8.5 (15°C)
Toluene	110.8	0.37	2.4	0.05 (16°C)
Ethanol	78.4	1.69	25.3	∞
Isopropanol (IPA)	82.5	1.64	17.9	∞
Ethyl ether	34.6	1.15	4.3	7.5 (20°C)

3.3: Knoevenagel condensation experiments

All reactions in this study were performed in batch mode in glass reactors. In a typical reaction, 2mmol of each carbonyl (furfural: 0.196g; HMF: 0.252g; levulinic acid: 0.232g) were reacted with 2mmol of malonic acid (0.208g) in 15ml pressure tubes (Chemglass; B in Figure 12). For the determination of conversion versus time profiles, a 50ml 2 neck flask with a reflux condenser (Chemglass; A in Figure 12) was used and samples were withdrawn with 0.1ml needles connected to a BD syringe. Hydrogenation of 2-((5-hydroxymethyl)furan-2-ylmethylene) malonic acid was performed in a 300ml Parr reactor (Parr; C in Figure 12). The three reactors are shown in Figure 12.

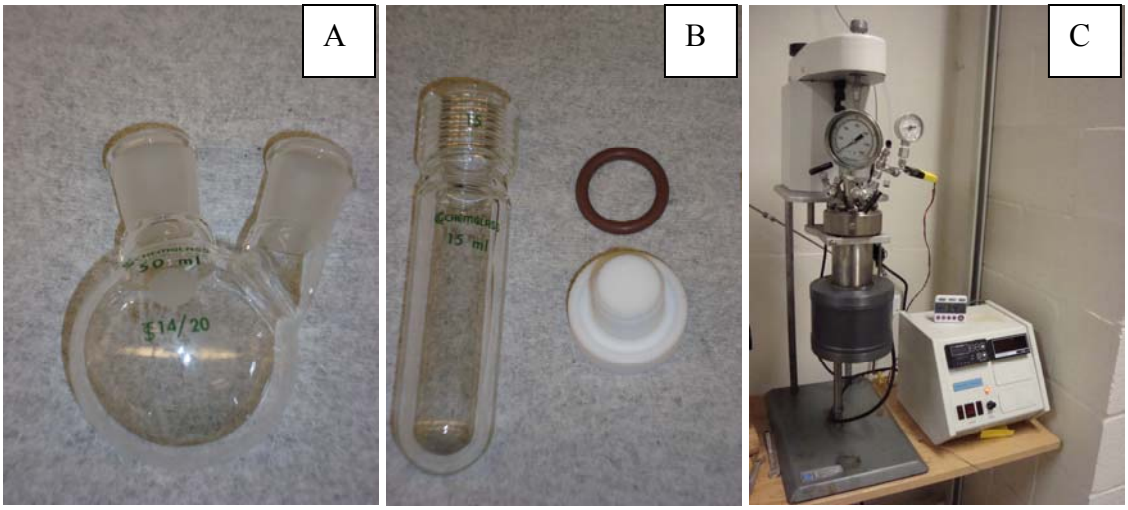


Figure 12: Reactors used (A: 50ml 2-neck flask; B: 15ml pressure tube; C: 300ml Parr reactor)

A typical experiment was performed by first heating a silicone oil bath to 80±1 °C. The reactants would then be introduced into the reactor with a stirrer and the reactor would be closed and immersed in the oil bath. The stirring rate of was maintained at 600rpm throughout. Experiments were performed for 5 hours except where noted. This time was determined by conversion versus time profiles using the 2 neck flasks, and it was found that the reaction approached a maximum after 5 hours for the reactants studied using both supported and homogeneous catalysts. The experimental set up is shown in Figure 13.

After the reaction time, the product was isolated and analyzed in the following manner: when the reaction was completed, the product mixture was first filtered and the catalyst recovered. The liquid fraction was then placed in a rotary evaporator to remove the solvent, and the remaining solid fraction was collected as product.

Figure 13: Reactor set up for Knoevenagel reaction

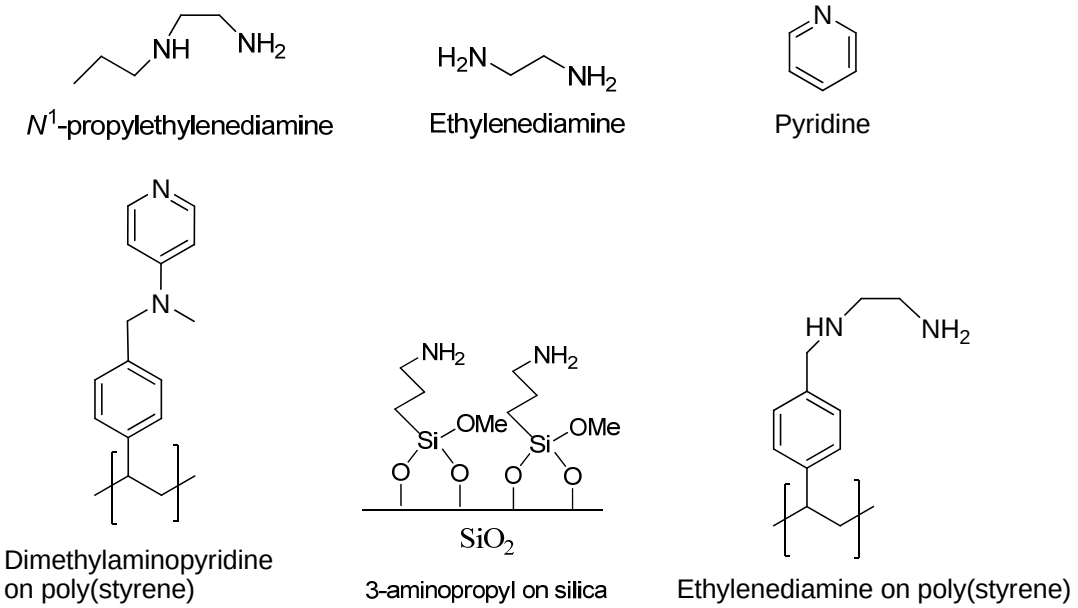
Reactant (HMF, furfural, levulinic acid) disappearance was tracked using dodecane as an internal standard with a Shimadzu GC 2010 Gas Chromatograph (GC) using a SHR5XLB column which had the following dimensions: 30m by 0.25mmID. This allowed for the determination of reactant conversion, but not selectivity since it was found that the product, being a carboxylic acid, did not elute on the GC column. However, reactant conversion and selectivity were determined by peak integration of ^{1}H NMR spectra on a Varian 300MHz instrument, using dimethyl sulfoxide-d_6 (DMSO) as the deuterated solvent. The product from the Knoeveangel reaction of malonic acid and HMF, 2-((5-hydroxymethyl)furan-2-ylmethylene) malonic acid, was characterized using Electron Spray Ionization (ESI) and Tandem Mass Spectrometry (TMS).

3.4: Hydrogenation of products

As 5 wt% Ru/Al_2O_3 was shown to be an effective catalyst for the hydrodeoxygenation (HDO) of lactic acid into propylene glycol [51], this catalyst was used in initial HDO experiments. The Knoevenagel product starting with HMF, 2-((5-hydroxymethyl)furan-2-ylmethylene)malonic acid, was used for these experiments. Five weight percent (5wt%) Ru/Al_2O_3 (catalyst) was obtained from SigmaAldrich and 125mg of Ru/Al_2O_3 were reduced at 450psi H_2 at 373K in a 300ml Parr reactor for 2 hours (C in Figure 12). Approximately 50mg of 2-((5-hydroxymethyl)furan-2-ylmethylene) malonic acid was dissolved in 25ml of water and this was charged into the reactor. The reaction was performed for 5 hours at 450 psi H_2 at 373 K. After the reaction was completed, the gas products were analyzed by GC and the liquid product was analyzed by ^1H NMR. The catalyst was filtered from the solution and the water was removed by overnight cooling at 333K. The solid residue was then analyzed by ^1H NMR.

3.5: Catalysts used in study

Catalysts used in this study were homogeneous amines (N-propylethane-1,2-diamine, ethylenediamine, pyridine), supported amines (Dimethylaminoyridine on poly(styrene), ethylenediamine on poly(styrene), 3-aminopropyl on silica), metal oxides (MgO, Al_2O_3), and layered double hydroxides (Hydrotalcite). These are shown schematically in Figure 14, and their chemical properties are given in Table 8. The supported catalysts were characterized by determining the BET and external surface areas and average pore sizes by nitrogen physisorption using a Micromeritics ASAP 2000 apparatus.



Solid Catalysts: **MgO; Al_2O_3; Hydrotalcite (Mg:Al =3)**

Figure 14: Catalysts used in study

3.5-1: Preparation of Hydrotalcite

Layered double hydroxides (LDH) belong to a group of anionic clays [83]. They exist as minerals, and Magnesium-Aluminium LDH's are commonly referred to as Hydrotalcite-like compounds or hydrotalcites [83]. They consist of positively charged $Mg(OH_2)$ layers with trivalent cations substituting divalent cations at octahedral sites in the hydroxide sheet [83]. The hydrotalcite used in this study was made in the following manner:

MgAl hydrotalcite based on $[Mg^{II}_{1-x}Al^{III}_{x}(OH)_2]^{x+}(CO_3^-)_x \cdot nH_2O$ was prepared by coprecipitation as follows: 500 ml of aqueous solution (A) containing the nitrates of Mg^{2+} and Al^{3+} was added slowly into an aqueous solution (C) of sodium carbonate (500 ml, 0.05 M). Simultaneously, the pH of the solution was adjusted at 10 by adding an aqueous solution (B) of sodium hydroxide (500 ml, 0.42 M) with vigorous stirring. The addition

was completed within 1 h. The slurry precipitated was then aged overnight at 80°C in the mother liquor. After the solution was cooled to room temperature, the precipitate was washed with de-ionized water until the solution was free of sodium ions. The washed filtration cake dried at 120°C for a night.

The hydrotalcite was activated to form mixed magnesium-aluminum oxide solid solution by calcining at 450°C under a CO_2-free nitrogen atmosphere. The temperature was raised at the rate of 2°C/min to reach 450°C and maintained for 4 h. After the sample was cooled to room temperature, a rehydration of the mixed oxide to form meixnerite, $[Mg_3Al(OH)_8]OH{\cdot}2H_2O$, was performed with decarbonated water at room temperature for 20 h under nitrogen flow. The sample was then filtered and dried at 120°C for 12 hours. Table 8 gives the physical and chemical properties of the catalysts used in the study.

Table 8: Physical and chemical properties of catalysts

Catalyst	**BET surface area (m^2/g)**	**Adsorption Avg. Pore Diameter (A)**	**External surface area (m^2/g)**	**Density (g/ml)**	**Amine Loading mmol N/g**
Ethylenediamine (h)	N/A	N/A	N/A	0.899	N/A
N-propylethylenediamine (h)	N/A	N/A	N/A	0.819	N/A
Pyridine (h)	N/A	N/A	N/A	0.978	N/A
Ethylenediamine on poly(styrene)	1.2	48.8	1.9	N/A	2.5-3.5
3-aminopropyl on silica	417.2	54.6	542.7	N/A	1
Dimethylamino pyridine on poly(styrene)	0.1	23.8	0.14	N/A	3
MgO	11.7	147	7.9	N/A	N/A
γ-Al_2O_3	212.0	66.5	220.0	N/A	N/A
Hydrotalcite	127.3	132.0	109.4	N/A	N/A

(h): homogeneous solution

3.5-2: Catalytic amounts used

The catalysts were used at a loading of 1.5mol% relative to the carbonyl compound throughout the study except where noted. Using a homogeneous ethylenediamine with the above ratio provided near to complete conversion and selectivity (100%) for both HMF and furfural. This ratio was chosen to have a medium that is sufficient to catalyze the Knoevenagel reaction, but not basic enough to cause self condensation of the aldehyde.

CHAPTER 4

RESULTS AND DISCUSSION

4.1: Effect of catalyst on furfural conversion

The catalysts in Figure 14 were tested to determine which would produce the highest yields and selectivity for 2-(furan-2-ylmethylene)malonic acid using the standard conditions described previously. In general the number of basic sites was held constant at 1.5mol% equivalent of catalyst to aldehyde. The experiments were conducted with 2mmol each of furfural and malonic acid in 10ml THF (inhibited with 250ppm butylated hydroxytoluene: BHT) for 5 hours at 80°C in a 15ml pressure tube except where noted. The results are given in Table 9. The ^{1}H and ^{13}C NMR spectra of the primary product, 2-(furan-2-ylmethylene)malonic acid, are shown in Figure 15 and Figure 16 respectively.

Table 9: Effect of catalyst on furfural conversion and selectivity

Catalyst	Quantity used (mg)	Furfural Conversion /%	Selectivity for di-acid /%
None	N/A	0	N/A
Ethylenediamine (h)	1.8	99	99
Ethylenediamine on poly(styrene)	10	58 ± 7	99
N-propylethylenediamine (h)	1.6	90±2	99
Pyridine (h)	2.2	0	N/A
3-aminopropyl on silica	30	53	99
Dimethylamino pyridine on poly(styrene) (DMAP)	10	0	N/A
MgO	30	2	n.d.
γ-Al_2O_3	30	14	n.d.
Hydrotalcite	30	2	100

(h): homogeneous solution

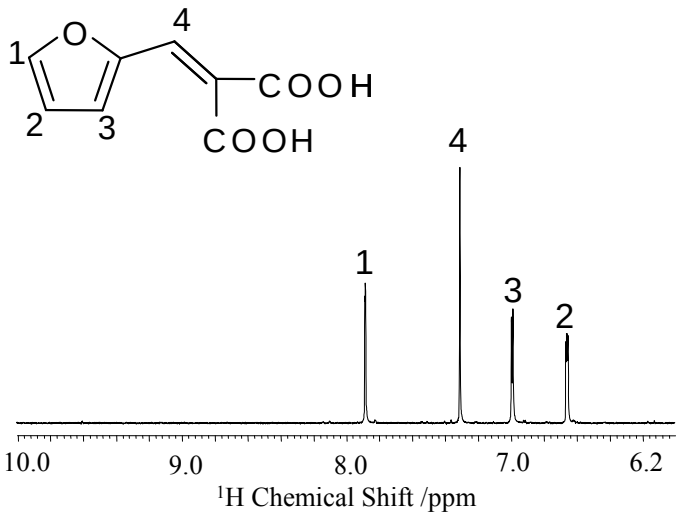


Figure 15: ^{1}H NMR of 2-(furan-2-ylmethylene)malonic acid in DMSO-d_6
Chemical shifts (300 MHz) δ ppm: 7.83 (d, H1), 7.3 (s, H4), 6.99 (d, H3), 6.67 (dd, H2)

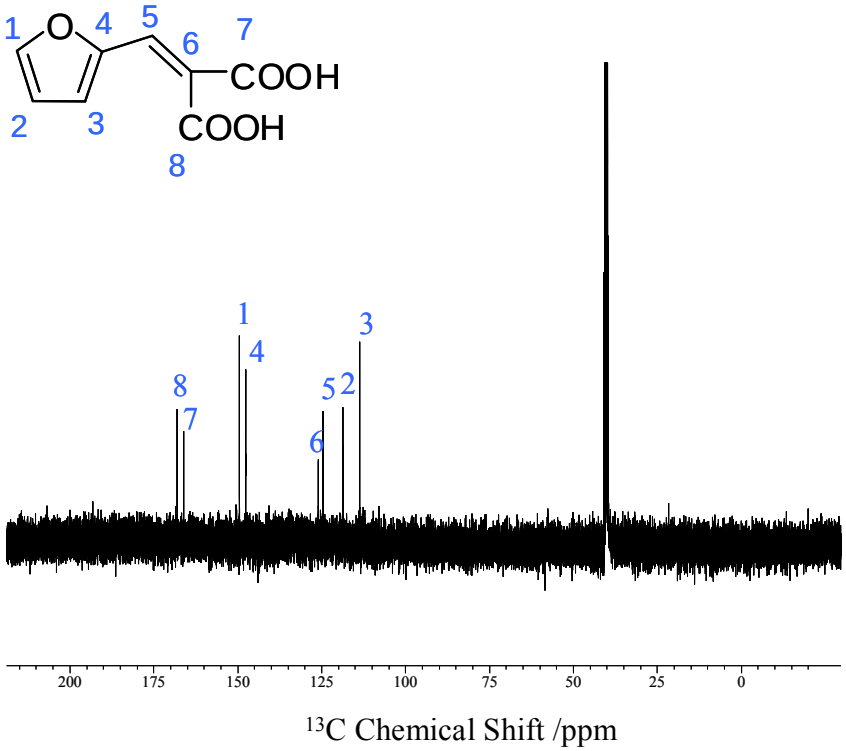
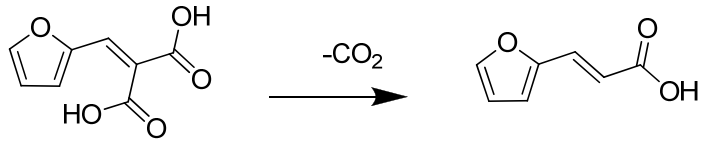


Figure 16: ^{13}C NMR of 2-(furan-2-ylmethylene)malonic acid in DMSO-d_6
Chemical shifts (300 MHz) δ ppm: 168, 166, 150, 147, 127, 125, 118, 113

Comparing the NMR spectra in Figure 15 and Figure 16 to a literature reference, it was found that the ^{13}C NMR chemical shifts of Figure 16 agreed within ±1ppm, while

the ^{1}H NMR chemical shifts in Figure 15 agreed to within ±0.3ppm [66]. This agreement validates that the product made is actually 2-(furan-2-ylmethylene)malonic acid.

The results from Table 9 show that in the absence of catalyst the reaction did not occur. Also, the heteroatomic amines (pyridine, DMAP) did not catalyze the reaction in the catalytic amounts used in this study. Previous authors used pyridine in higher catalytic amounts [84], but the yields were 21% (30% selectivity) [85]. Also the supported DMAP did not work under these conditions even though it contained two types of tertiary amine sites: aromatic and alkyl. It was found by previous authors that adding a small quantity of piperidine (a secondary amine) to the pyridine mixture improved the conversion and yield of expected products [85, 86]. Using larger pyridine concentrations (molar ratio of butyraldehyde: pyridine = 1:1) the yields of di-acid product were improved: 75-80% (95% selectivity) [85]. However, pyridine has been noted to catalyze the decarboxylation reaction, giving unsaturated mono-acids (α-β and β-γ unsaturated mono-acids as well) instead of di-acids with yields of 60-90% [87]. Under the conditions used in this study, selectivity for the di-acid did not fall below 97% except for experiments performed in water as solvent. Thus the decarboxylation reaction did not occur to a large extent under these conditions. The decarboxylation reaction is given in Figure 17 and the ^{1}H NMR of the furfural mono acid ((E)-3-(furan-2-yl)acrylic acid) is given in Figure 18. It is also important to note that decarboxylation reactions are undesirable for the production of a fuel additive, since these reactions result in the loss of a carbon atom, and the target compounds are ideally in the gasoline range (C_8-C_9).



2-(furan-2-ylmethylene)malonic acid (E)-3-(furan-2-yl)acrylic acid

Figure 17: Decarboxylation reaction of 2-(furan-2-ylmethylene)malonic acid

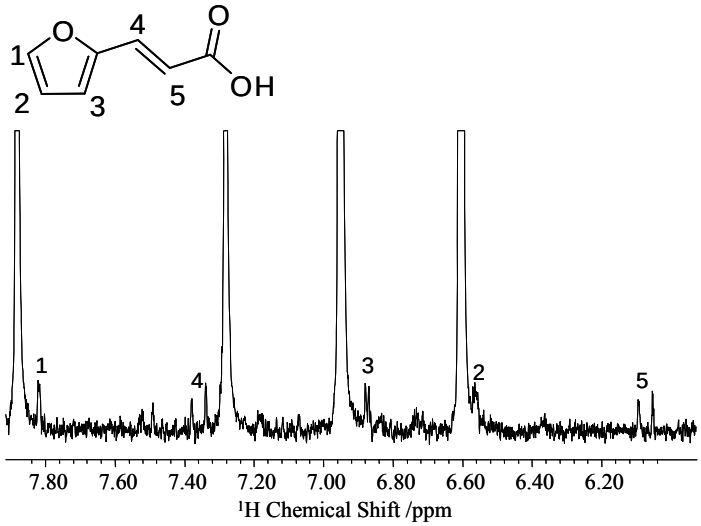


Figure 18: ^{1}H NMR of (E)-2-(furan-2-yl)acrylic acid
Chemical shifts (300 MHz, DMSO) δ ppm: 7.83(d, H1), 6.62 (dd, H2), 6.92 (d, H3), 6.12 (d, H5), 6.16 (d, H4)

Among the homogeneous amines tested, ethylenediamine gave the highest conversion and selectivity (99% selectivity and conversion), followed by propylethylenediamine (90% selectivity, 99% conversion). The difference could be due to the fact that ethylenediamine contains two primary amines sites, while propylethylenediamine, has primary and secondary amine sites. This implies that primary amines are better catalysts than secondary amines for this reaction. The kinetic profile for a homogeneous ethylenediamine experiment is shown in Figure 19.

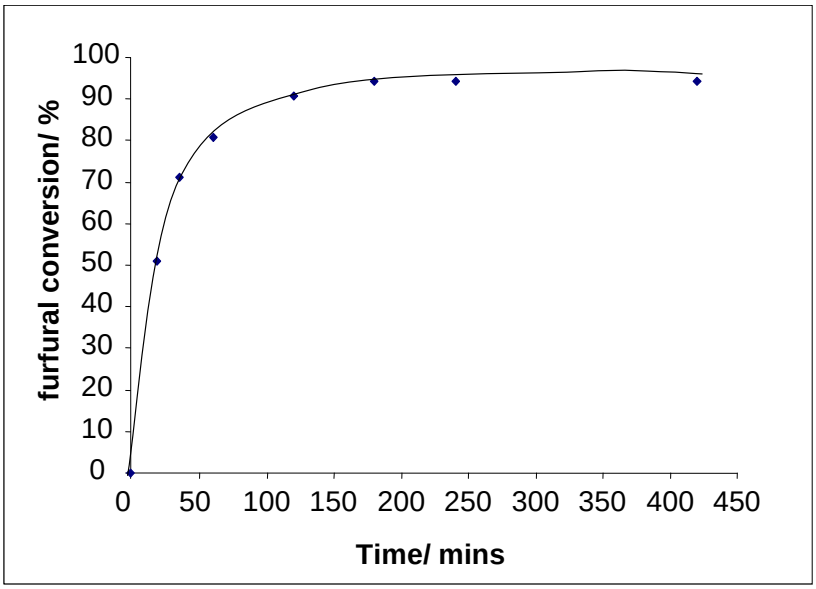


Figure 19: Kinetic profile of furfural conversion into 2-(furan-2-ylmethylene)malonic acid using homogeneous ethylenediamine

The final conversion after 5 hours using the homogeneous ethylenediamine in Figure 19 is 95% which is 4% less than the value obtained in a pressure tube (99%). With the supported amines, the conversion was approximately the same for ethylenediamine on poly(styrene) and 3-aminopropyl on silica, and the selectivities for the di-acid were both high (99%). The error margin was determined by repeating the experiments several times and averaging the values and was determined to be ±7%. Drying the supported ethylenediamine catalyst for an hour under vacuum resulted in a conversion of 61%, but this is within the error range of the experiments conducted (58±7%). This shows that the presence of any physisorbed water did not appreciably affect the catalyst activity.

To determine the effect of increasing the catalyst to reactant ratio, experiments were conducted using 2mmol furfural and 2mmol malonic acid and increasing the mass of catalyst used from 1.5mol% to 6.0mol% equivalent of catalyst to aldehyde. The results are shown in Figure 20.

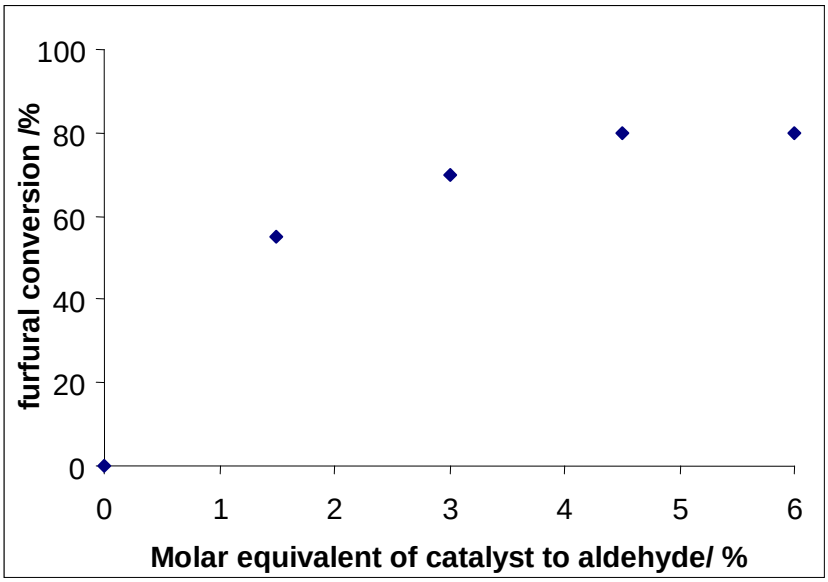


Figure 20: Effect of increasing molar ratio of furfural: ethylenediamine on poly(styrene) ratio on conversion

The results in Figure 20 show that increasing the molar ratio of furfural to basic sites on ethylenediamine lead to an increase in conversion, but the conversion approached a limiting value of 80±1 %. It is assumed that the error is the same at 7% for these experiments. Possible reasons for the variations in catalyst activity are suggested in a later section on catalyst deactivation (Section 4-5). It has been noted in the literature that using excessive amounts of base causes self condensation of aldehydes [88]. However, side products were not observed in our work.

The solid oxides (MgO and γ-Al_2O_3) did not catalyze the reaction as well as the other catalysts. Among these catalysts (Table 8), MgO has the lowest BET and external surface area but possesses the largest pore diameter. These factors are possible reasons for the low activity in the MgO as its low surface area could be lead to the basic sites being inaccessible to the reactants. The reaction was repeated after calcining the MgO at 600°C, and the yields were still low after 5 hours (<10%). The reaction was left to run for 24 hours and the yield increased to 10%. Moison and co-workers were able to catalyze

the Knovenagel reaction with MgO using several aromatic aldehydes and malononitriles with 90%+ yield of expected olefinic product [89]. However, the molar amount of MgO used was greater (90mol% MgO equivalent to aldehyde) than the amount used in this study (0.075mol% MgO equivalent to aldehyde) [89]. Nonetheless, MgO functions as a Lewis base, with the oxide ion (O^{2-}) donating its pair of electrons to abstract a proton from the methylene group, while the intermediate anion formed is complexed with the cation Mg^{2+} [89].

The catalytic activity of MgO is affected by atmospheric H_2O and CO_2 species since these species tend to cover the catalyst surface making the basic electron pairs inaccesible [90]. Thus pretreatment is necessary, and a review by Hattori discusses the effect of pretreatment temperature on the reactivity of MgO for several reactions [90]. For these reasons, the MgO was calcined at 600°C and re-tested, but there were no increases in conversion.

Reasons for the low activity of the hydrotalcite in THF (2%) are unclear. However, when 30mg of the hydrotalcite was used as a catalyst with 2mmol each of malonic acid and furfural in 10ml water for 12 hours produced a furfural conversion of 42% with 100% selectivity. This is in agreement with Ebitani and co-workers who used a reconstructed hydrotalcite to catalyze the Knoevenagel reaction in water [91], where yields of 70-90% were obtained [91]. Since the hydrotalcite catalyzes the reaction in water via the hydroxide ions ($-OH^-$) in its lattice, it is supposed that the hydroxide ions are not available in THF to catalyze the reaction.

4.1-1: Effect of solvent on furfural conversion

As the poly(styrene) supported ethylenediamine on poly(styrene) gave a higher conversion than the 3-aminopropyl silica supported catalyst with less catalyst (10mg vs. 30mg) in THF, the supported ethylendiamine was studied further to investigate the effect of the solvents on promoting the Knovenagel reaction. Ten milliliters (10ml) of each solvent in Table 7 was used with 1.5mol% equivalent of catalyst and 2mmol each of furfural and malonic acid in 15ml pressure tubes for 5 hours. Conversions were measured with GC and tracked using furfural disappearance with dodecane as an internal standard except when water was used as a solvent. Furthermore, toluene gave a solid precipitate in the solution at the end of 5 hours. This solid was collected by filtration and analyzed by ^{1}H NMR. Also, using water as solvent, the conversion was determined by ^{1}H NMR. The results are shown in Table 10, with the solvents arranged in order of increasing dielectric constant.

Table 10: Conversion and selectivity for solvents used with Knoevenagel reaction of furfural and malonic acid

Solvent	Conversion /%	Selectivity for di-acid /% (liquid phase)	Selectivity for di-acid /% (solid phase)	Dielectric constant
Toluene	31	0	100	2.4
Ethyl ether	20	99	N/A	4.3
Ethyl acetate	42	99	N/A	6.0
THF	51	99	N/A	7.5
Isopropanol (IPA)	48	68	N/A	18.3
Ethanol	44	70	N/A	24.3
Water	30	70	N/A	80

a) Ethanol

Using ethanol, a side product was identified by GCMS that followed the reaction shown in Figure 21.

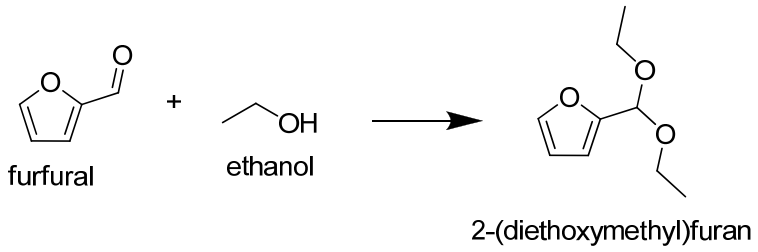


Figure 21: Side products identified by GCMS using ethanol as solvent

Although identified by GCMS, the product shown in Figure 21 was in low yield (<20% selectivity). The Knoevenagel product of furfural with malonic acid was identified in reasonably high selectivity (70%), but the overall conversion (44%) was somewhat low. Possible reasons for the low conversion are due to the interactions of the protic

solvent with the polystyrene support. Thus ethanol is not a particularly good solvent using the polystyrene supported catalyst.

b) THF

Using THF as solvent, furfural, malonic acid and n-dodecane dissolved on shaking. No precipitates were identified under these conditions, and the final conversion after 5 hours was 51%. The 99% selectivity is good, with the decarboxylated product in 1% selectivity. Furthermore, the THF solvent was recovered easily by rota-evaporation after the reaction. This recycle ability, together with its ability to convert furfural without reacting with it, makes THF a good solvent for this reaction.

c) IPA

As was the case with ethanol, a side product was identified in the ^{1}H NMR spectrum which matches the product shown in Figure 22. Nonetheless, the expected Knoevenagel product was identified in the ^{1}H NMR spectrum, and the overall conversion (48% conversion, 68% selectivity) was slightly higher than ethanol (44% conversion, 70% selectivity).

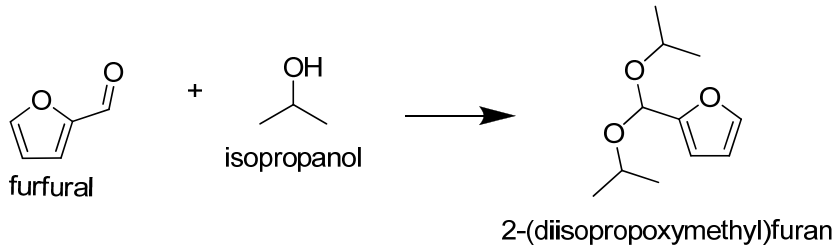


Figure 22: Side reaction between furfural and IPA

d) Ethyl acetate

This solvent gave a moderate conversion (40% conversion, 99% conversion) and no side products were identified. This experiment was repeated for 5 hours at 80°C with the same catalytic amount and yielded the same values for conversion and selectivity.

This indicates that increasing reaction time had no effect on the ultimate conversion. It is not clear if the catalytic activity is reduced with time or if the catalytic activity is inhibited by the reaction product.

e) Water

Using water as a solvent, the conversion for furfural was 30% with a 60% selectivity for the di-acid, 40% selectivity for the trans mono-acid. It is interesting that the reaction is facilitated in water, even though it is a product of the reaction. Using the poly(styrene) supported ethylenediamine in water, it was noticed that the catalyst was spread along the sides of the pressure tube and at the meniscus in the reaction tube. This repulsion is probably due to the hydrophobicity of the poly(styrene) support. The experiment was repeated using 3mol% equivalent of 3-aminopropyl on silica to see if the hydrophilic silica would improve yields of product. The result was 17% conversion with 100% selectivity. Thus the selectivity increased but the overall conversion decreased. This is a somewhat unexpected trend (the conversion reduces by using a hydrophilic supported amine). Using 2μl (1.5 mol% equivalent) of homogeneous ethylenediamine in water for 5 hours at 80°C, the conversion was 27% with 100% selectivity. This shows that water is not a good solvent for the reaction using amines, since complete furfural conversion can be achieved using this amount of homogeneous ethylenediamine in THF.

f) Toluene

Using toluene as solvent, the furfural and n-dodecane dissolved on shaking, but the malonic acid remained as a solid at the bottom of the pressure tube. After 5 hours, a solid was present at the bottom of the tube. After filtration and drying at 105°C for 15 minutes, the mass of the solid was 137mg, of which 10mg is assumed to be catalyst. The

image of the precipitate in the test tube is shown in Figure 23 and the ^{1}H NMR spectrum of the solid precipitate is given in Figure 24.

Figure 23: Furfural precipitate in toluene

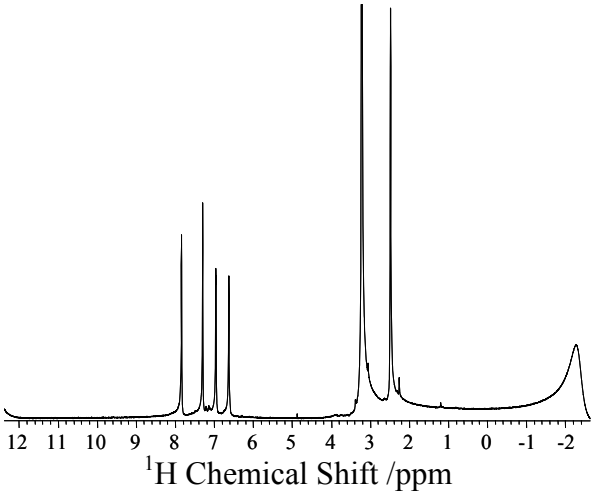


Figure 24: ^{1}H NMR spectrum of precipitate using toluene as solvent dissolved in DMSO-d_6
Chemical shifts /ppm: 7.84, 7.29, 6.96, 6.62, 3.2, 2.49, -2 (14)

Comparing the spectra in Figure 15 and Figure 24, the resonances in the aromatic region ($6<\delta<9$ppm) agree to within ±0.05ppm. This shows that the solid precipitate is 2-(furan-2-ylmethylene)malonic acid. The resonance at δ=3.2ppm corresponds to the protons in water and the resonance at δ=2.49ppm is due to the protons in DMSO. The

resonance at δ=14ppm corresponds to the carboxylic acid group in 2-(furan-2-ylmethylene)malonic acid. Figure 24 also shows that there is no furfural present in the solid precipitate (Chemical shifts of furfural δ/ppm: 9.7, 7.8, 7.3, and 6.7) or decarboxylation products.

Examining the liquid phase showed the presence of furfural, but not 2-(furan-2-ylmethylene)malonic acid. Under these conditions, toluene was the only solvent which gave a precipitate of the solvents tested for furfural. Reasons for the precipitation of the product are possibly due to the repulsions between the furfural product and toluene since the product contains two polar acid groups which could repel the aromatic toluene. Furthermore, toluene is the only apolar solvent among the solvents tested.

g) Ethyl ether

Using ethyl ether, the conversion was low (20%) and no precipitates were seen. Due to the low boiling point of ethyl ether (35°C), it was easy to remove the solvent. However, ethyl ether is known to form explosive peroxides on storage, and thus its use cannot be recommended on a large scale.

These results show that certain solvents (e.g. toluene) can influence 2-(furan-2-ylmethylene)malonic acid product separation from a mixture, while other solvents can be recovered in high yield at the end of the reaction (e.g. THF).

4-1.2: Effect of increasing the concentration of furfural and malonic acid on furfural conversion in 10ml of THF solvent

For the production of fuels on an industrial scale it is desirable to conduct reactions at high reactant concentrations. Therefore, reactions were performed in which the mass of each species (furfural, malonic acid and poly(styrene) supported

ethylenediamine) was increased by a factor of 5 from the standard conditions. In all experiments, the volume of solvent (10ml of THF) remained the same. Two reactions were performed in a 50 ml two neck flask for 4 hours, and one in a 15 ml pressure tube. Two additional reactions with homogeneous N-propylethylenediamine were performed in 15 ml pressure tubes for 4 hours. This was done to study the effect of the active amine group since the supported ethylenediamine and propylethyenediamine both contain primary and secondary amine sites. However, this is an approximation as the supported ethylenediamine has an aromatic ring adjacent to the secondary amine, which could provide a steric hindrance as well as interfere with the lone pair of electrons on the secondary nitrogen. These reactions were tracked by furfural disappearance with dodecane as an internal standard using GC. These results are shown in Figure 25.

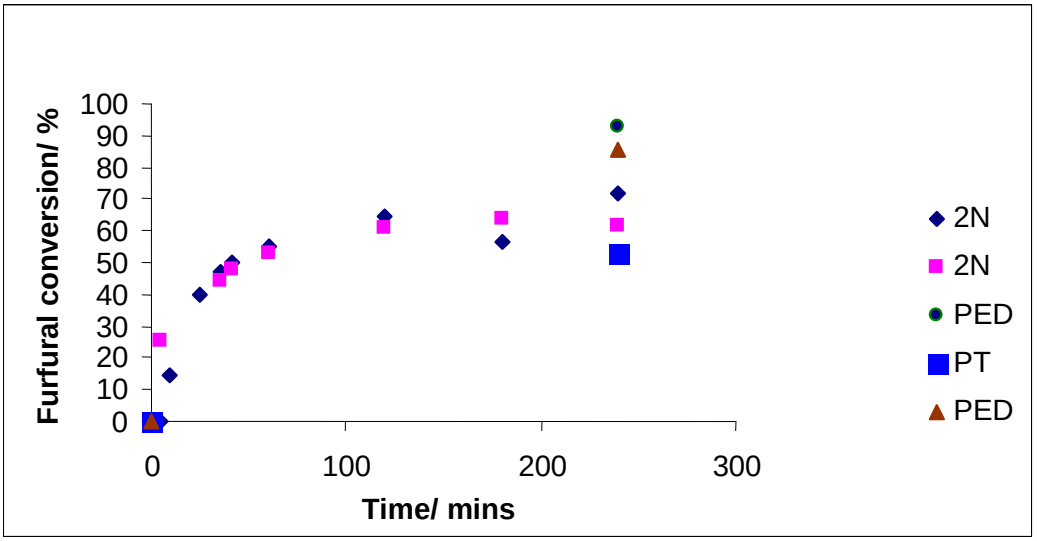


Figure 25: Profiles for concentration changes in furfural-malonic acid-THF reactions
Legend:
2N: 50ml 2 neck flask with 30mg ethylenediamine on poly(styrene)
PED: 15ml pressure tube with 18µl homogeneous propylethylenediamine
PT: 30mg ethylenediamine on poly(styrene) in a pressure tube

By increasing the concentration of the reactants and the amount of catalyst in the heterogeneous reaction by a factor of 5, the conversion increased from an average value of 57% (1.5mol% equivalent of aldehyde using 2mmol furfural to 1.5mol% equivalent of aldehyde using 10mmol furfural) to an average of 65% (Figure 25). In the experiments in the time profiles, product selectivity was not determined, since the compound being a di-acid did not elute on the chromatograph. However, the experiment was repeated in a pressure tube (10mmol each furfural and malonic acid) for 5 hours under the same conditions. The conversion using ^{1}H NMR was 74%, with 99% selectivity so it is reasonable to assume that the expected product is forming, and tracking disappearance of the reactant by GC is possible.

Figure 25 also shows that the homogeneous propylethylenediamine gave a higher conversion (90% vs. 65%) than the supported amine. The difference between the homogeneously and heterogeneously catalyzed reactions indicates that steric hindrances due to accesibility exist for furfural. From these experiments, the results are reproducible for the heterogeneous reaction (blue and pink markers) and the conversion obtained in the pressure tubes is comparable to the conversion obtained in the 2 neck flasks (square blue and pink markers).

4.2: Effect of catalyst on HMF conversion

The catalysts listed in Table 8 were screened for their ability to convert HMF into 2-((5-hydroxymethyl)furan-2-ylmethylene) malonic acid. As was used for furfural, the molar equivalent of catalyst to HMF was maintained constant at 1.5mol%. The experiments were conducted with 2mmol each of HMF and malonic acid in 10ml THF

(inhibited with 250ppm BHT) for 5 hours at 80°C in a 15ml pressure tube except where noted. The results are summarized in Table 11.

Table 11: Effect of catalyst on HMF conversion and selectivity

Catalyst	Catalyst Quantity (mg)	HMF Conversion /%	Selectivity for di-acid
None	N/A	0	N/A
Ethylenediamine (h)	1.6	100	99
Ethylenediamine on poly(styrene)	10	65 ± 5	99
N-propylethylenediamine (h)	1.8	90	97
Pyridine	2.2	0	N/A
3-aminopropyl on silica	30	74	97
Dimethylamino pyridine on poly(styrene) (DMAP)	10	10	100
MgO	30	2	N/A
γ-Al_2O_3	30	1	N/A
Hydrotalcite	30	2	N/A

(h): homogeneous

The pure product (100% conversion) was a light yellow to cream solid at room temperature. A sample of this product was analyzed via Tandem Mass Spectrometry and Electron Spray Ionization. The results are shown in Figure 26.

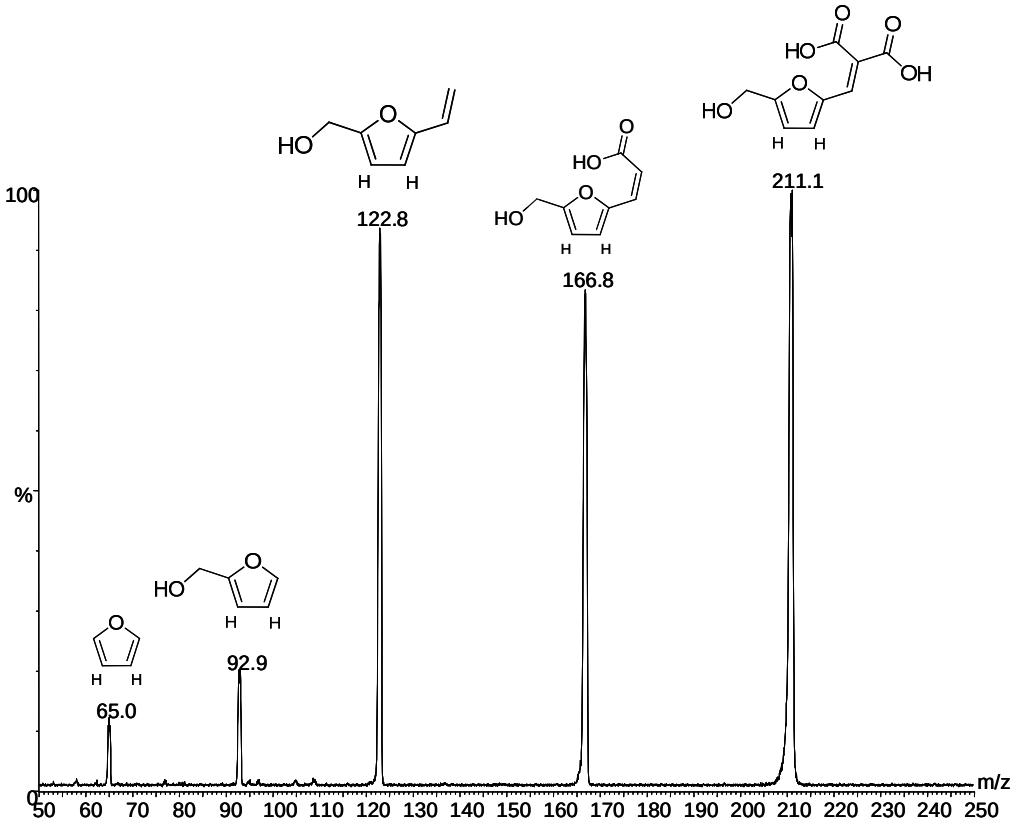


Figure 26: Electron Spray Ionization spectra of 2-((5-(hydroxymethyl)furan-2-yl)methylene malonic acid (20V collision)

The peaks in Figure 26 correspond to the molecular weight of the ion and the structure of the ion is shown above each peak. These results confirm the structure of 2-((5-(hydroxymethyl)furan-2-yl)methylene malonic acid. A ^{13}C NMR spectra and an ^{1}H NMR spectra was obtained of 2-((5-(hydroxymethyl)furan-2-yl)methylene malonic acid and are shown in Figure 27 and Figure 28 respectively.

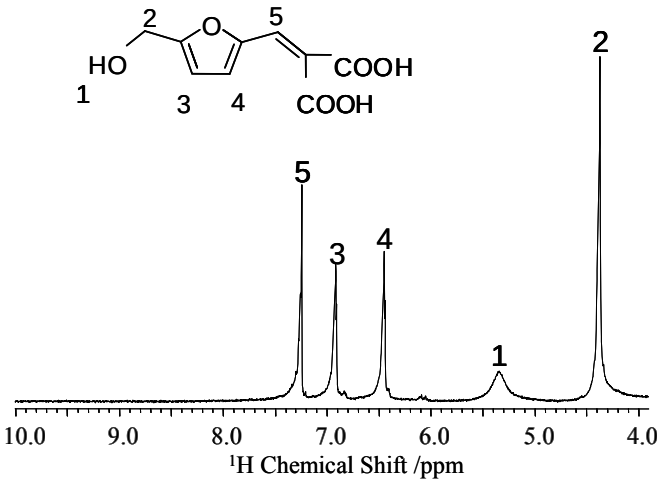


Figure 27: ^{1}H NMR of 2-((5-hydroxymethyl)furan-2-ylmethylene)malonic acid in DMSO-d_6
Chemical shifts (300 MHz) δ ppm: 5.35 (s, H1), 4.38 (s, H2), 6.92 (d, H3), 6.46 (d, H4), 7.25 (s, H5)

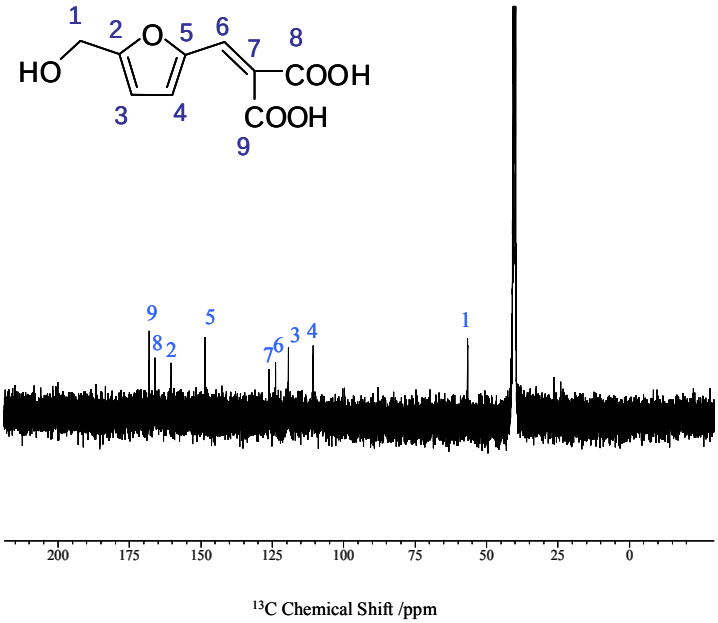


Figure 28: ^{13}C NMR of 2-((5-hydroxymethyl)furan-2-ylmethylene)malonic acid in DMSO-d_6
Chemical shifts (300MHz): 168, 166, 160, 149, 126, 124, 119, 111, 56

The results in Table 11 show that the ethylendiamine catalyzed the reaction with a higher conversion and selectivity for the di-acid than the propylethylenediamine. Also, the results show that the conversions using either of the two homogeneous amines are

higher than those obtained from the supported amines. A similar trend was also seen with furfural. It was noticed that the silica supported 3-aminopropyl gave a higher conversion, but lower selectivity for the di-acid than the ethylenediamine catalyst on polystyrene. The conversion for HMF with both 3-aminopropyl and ethylenediamine on poly(styrene) were both higher for HMF than furfural. This suggests that the hydroxymethyl group facilitates the conversion possibly through hydrogen bonding with the secondary amine group in the supported ethylenediamine and also with surface silanols on the silica surface to improve the chances of the HMF accessing the catalysts' active sites.

As was seen for reactions with furfural, the tertiary bases did not work as well in the conditions in this study. Thus DMAP gave 10% HMF conversion and pyridine did not show any conversion with after 5 hours.

Among the solid catalysts MgO and γ-Al_2O_3, the yields were very low, which was also seen for furfural. The reasons for the low activities are assumed to be due to inaccessibility of the basic sites on MgO and acidic sites on γ-Al_2O_3.

The profile of HMF conversion was obtained by tracking HMF disappearance with GC using dodecane as an internal standard in a 2-neck flask and 10mg of ethylendiamine on poly(styrene) as catalyst. The profile is shown in Figure 29. The final conversion obtained (70%) is within the error range (65±5%) of the experiments which were performed in a pressure tube. Also the conversions analyzed by GC agreed with the conversions analyzed by ^{1}H NMR. The data in Figure 29 shows that most of the conversion occurs in the first hour (approx 53% converted), after which the conversion approaches a limiting value. However, the reaction is not thermodynamically limited since the reaction can go to 100% conversion with the homogeneous ethylenediamine

(Table 11). This implies that the support is interfering with the conversion possibly via limiting the accessibility to active sites.

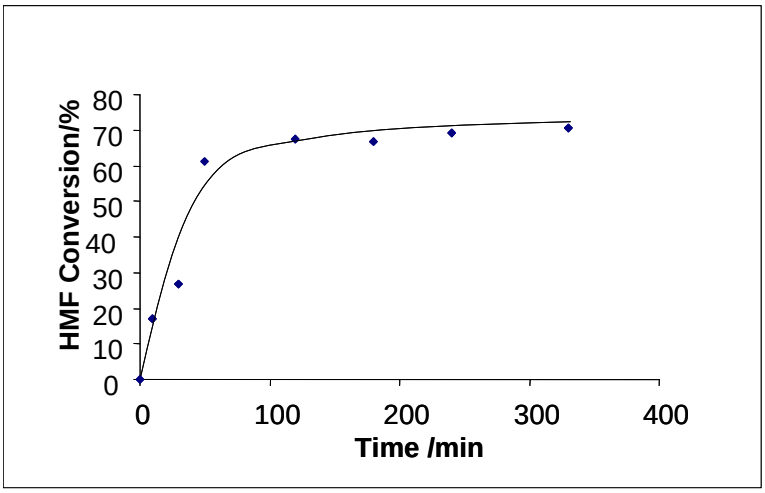


Figure 29: Profile of HMF conversion with time

To examine the effect of increasing the ratio of basic sites to aldehydes, experiments were conducted using 2mmol HMF and 2mmol malonic acid and increasing reactant to catalyst (ethylendiamine on poly(styrene)) ratios. For instance, a molar equivalent of 1.5mol% corresponded to an experiment with 2mmol HMF and 10mg catalyst. These experiments were conducted for 5 hours at 80°C in a 15ml pressure tube. The final conversions after 5 hours for the different ratios are shown in Figure 30.

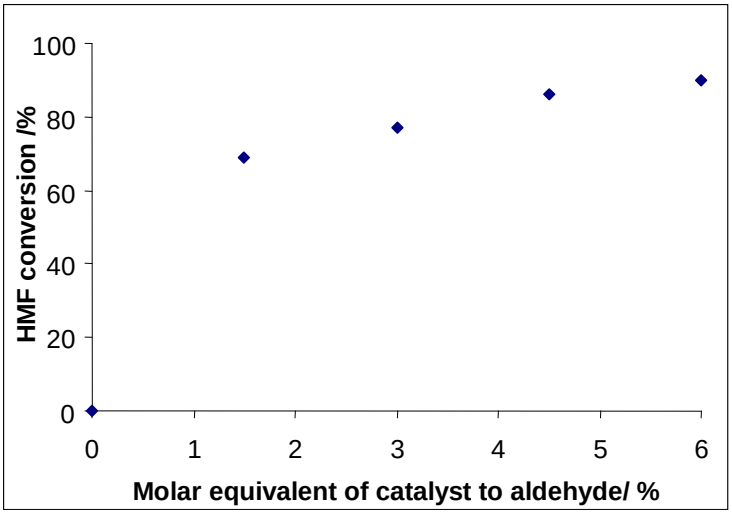


Figure 30: Effect of increasing molar equivalent of basic sites on (ethylendiamine on poly(styrene)) catalyst on HMF conversion.

Figure 30 shows that increasing the molar equivalent of basic sites on ethylendiamine on poly(styrene) from 1.5mol% to 6mol% catalyst increased the conversion from approximately 65% to 90%. Selectivities for the di-acid were high (97-99%) throughout. Although this was expected, the increase in conversion with increasing basic site to aldehyde ratio was higher for HMF than for furfural with the same catalyst (Figure 20). This result implies that higher conversions are achieved with ethylendiamine on poly(styrene) with HMF than with furfural. Also, these results imply that greater than 6mol% of supported ethylenediamine on poly(styrene) are required to achieve the same conversion as 1.5mol% homogeneous ethylenediamine. Since there are more basic sites with 6mol% of supported ethylenediamine on poly(styrene) than 1.5mol% homogeneous amine, reasons for the activity difference are due to accessibility of the basic sites on the supported catalyst.

4.2-1: Effect of solvent on HMF conversion

The solvents listed in Table 7 were utilized in the Knoevenagel reaction of HMF and malonic acid to determine the effect of protic solvents (e.g. alcohols), ethers and esters. The poly(styrene) supported ethylenediamine was used in these reactions at a molar equivalent of 1.5mol% relative to HMF. The solvents listed in Table 7 were used in separate runs with 10mg of ethylenediamine on poly(styrene) and 2mmol each of furfural and malonic acid in 15ml pressure tubes for 4 hours at 80°C. Conversions were measured with GC and tracked using HMF disappearance with n-dodecane as an internal standard and selectivity for the di-acid was determined by ^{1}H NMR. During the reaction, some solvents gave a precipitate. This was separated at the end of the reaction by filtration and analyzed by ^{1}H NMR. The results are presented in Table 12 with both conversion and selectivity for the liquid and solid phases where applicable.

Table 12: Effect of solvent on HMF conversion and selectivity

Solvent	**Conversion /%**	**Selectivity for di-acid /% (liquid phase)**	**Selectivity for di-acid /% (solid phase)**	**Dielectric constant**
Toluene	15	0	15	2.4
Ethyl ether	31	2	98	4.3
Ethyl acetate	40	9	100	6.0
THF	65	99	N/A	7.5
Isopropanol (IPA)	30	70	N/A	18.3
Ethanol	66	70	N/A	24.3
Water	15	80	N/A	80

a) Ethanol

Using ethanol, a side product was identified by ^{1}H NMR that followed the reaction shown in Figure 31 in approximately 30% selectivity.

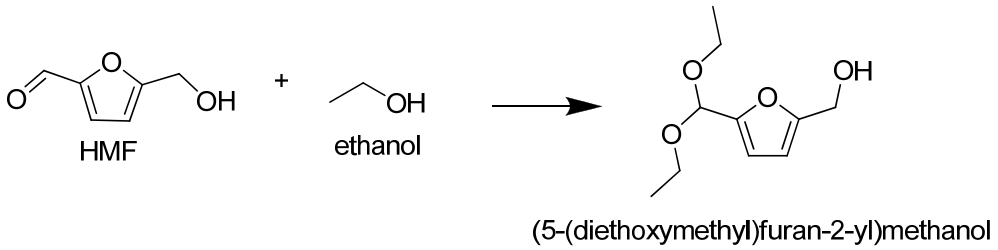


Figure 31: Side reaction between HMF and ethanol

Conversion of HMF was high with ethanol and the selectivity was reduced due to the reaction in Figure 31. Compared to furfural (44% conversion, 70% selectivity), HMF in ethanol gave a higher overall yield (66% conversion, 70% selectivity).

b) THF

Using THF as a solvent, the reaction proceeded in high selectivity (97-99%) with the decarboxylation product identified in low yields. HMF conversion in THF was the highest among the highest among the solvents tested. Using the homogeneous ethylenediamine in 1.5mol% a solid precipitated out of the solution.

c) IPA

With IPA as solvent, the conversion was somewhat low (30%) and did not fit the trend seen with furfural as solvent (higher conversion with IPA than ethanol). However, the selectivity was the same for both ethanol and IPA with HMF (70%).

d) Ethyl acetate

With ethyl acetate as solvent, it was found that a white solid precipitated out of the solution after 2 hours. After the reaction was completed, this solid was filtered and analyzed by ^{1}H NMR. The spectrum of the precipitate is given in Figure 32. The liquid

phase was also analyzed by ^{1}H NMR and did not show 2-((5-(hydroxymethyl)furan-2-yl)methylene malonic acid.

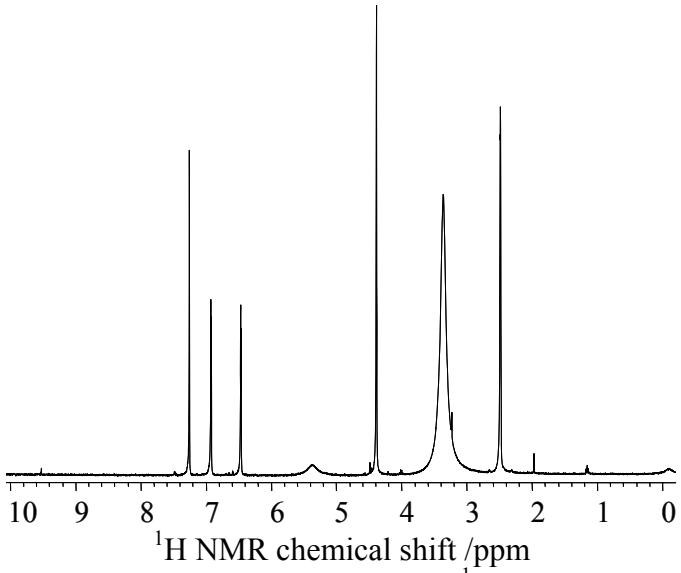


Figure 32: Precipitate from ethyl acetate analyzed by ^{1}H NMR in DMSO-d_6

Comparing the spectra in Figure 32 to Figure 27, the resonances are identical in the aromatic region (6<δ<9ppm) and for hydroxymethyl group (δ=4.4ppm). Therefore, the precipitate is 2-((5-hydroxymethyl)furan-2-ylmethylene)malonic acid. The liquid fraction was analyzed and it contained small amounts of HMF, malonic acid and HMF di-acid (9%). Thus ethyl acetate is a convenient solvent for the precipitation of 2-((5-hydroxymethyl)furan-2-ylmethylene)malonic acid.

e) Water

With water as a solvent, the ^{1}H-NMR spectra of the product showed 15% HMF conversion with 80% selectivity for the di-acid. Small amounts of levulinic acid (<5%), which is formed from the acid catalyzed hydrolysis of HMF, was identified among products.

f) Toluene

Using toluene, a black solid began forming within 1 hour at the bottom of the tube, which gave the appearance of a non-homogeneous phase. The picture in Figure 33 shows the product mixture after 5 hours.

Figure 33: Picture of solid product in pressure tube after Knoevenagel reaction of HMF and malonic acid in toluene

The black solid phase was very viscous. It was insoluble in toluene, soluble in DMSO-d_6 and partially soluble in water. The ^{1}H NMR spectrum of the solid is shown in Figure 34.

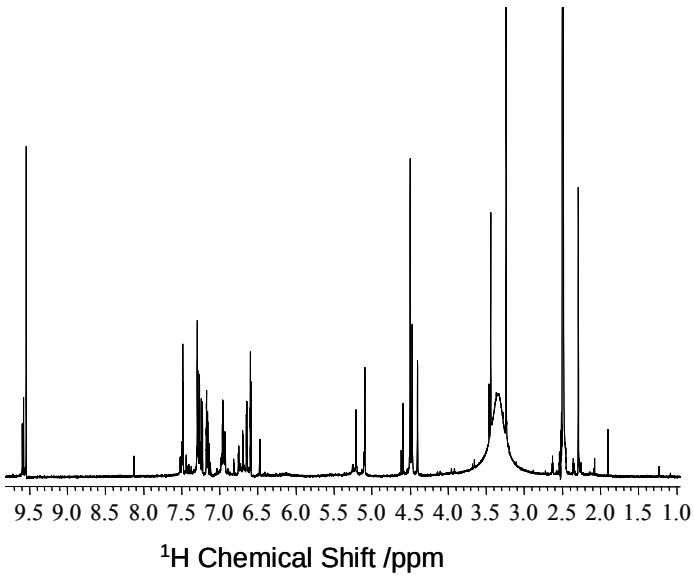


Figure 34: ^{1}H NMR of the solid phase from the Knoevenagel reaction between HMF and malonic acid in toluene (in DMSO-d_6)

The spectrum in Figure 34 shows that several compounds are present. The ^{1}H NMR of the reactants, solvent and expected product is shown in Figure 35.

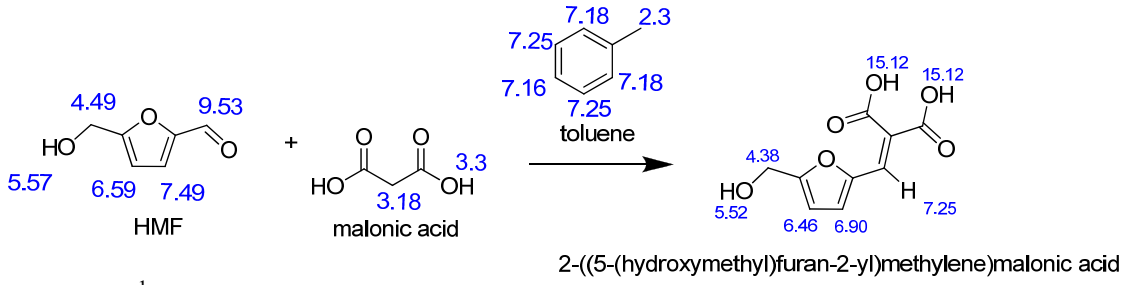


Figure 35: ^{1}H NMR of HMF, malonic acid, toluene and expected Knoevenagel product (numbers above molecules refer to ^{1}H chemical shifts in DMSO-d_6)

Therefore, in Figure 34 malonic acid is present with the carboxylic –OH groups in the range 3<δ<3.3ppm. However, there is a singlet at δ=3.4ppm that is unknown but the general range is for enols [92]. An expansion of the region from 4-10ppm is shown in Figure 36.

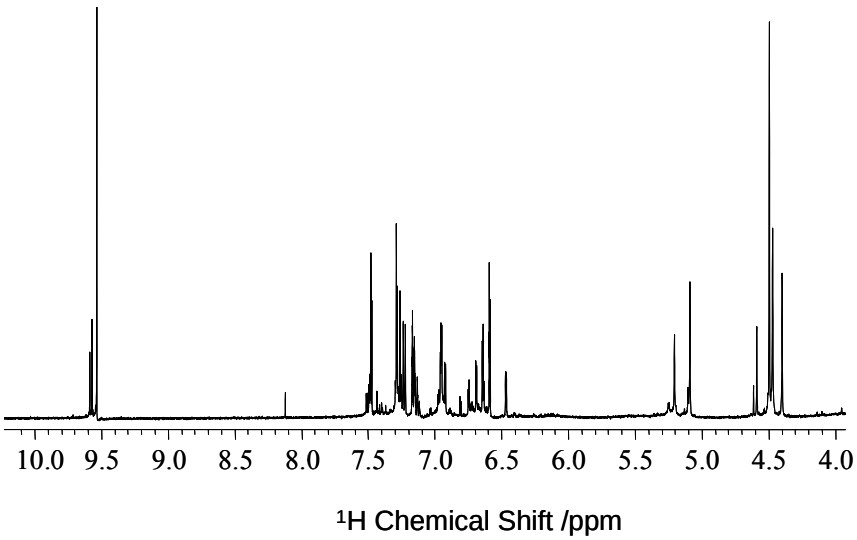


Figure 36: Expanded ^{1}H NMR of solid precipitate in toluene

With respect to the expected Knoevenagel product, it is possible that the compound was formed, but it is not entirely clear from the resonances in Figure 36. Figure 36 also shows that there is some toluene (δ=7.1-7.2ppm) and HMF present (δ=9.5, 7.5, 6.5, 4.5ppm). However, there is more than one aldehyde present (δ=9.6ppm), and there are distinct resonances at δ=5.1 and 5.2ppm. This region is for alkene species [92]. Furthermore, in the region where the aliphatic alcohols (e.g. hydroxymethyl group in HMF at 4.4ppm) appear (4-5ppm), there are several new resonances. Thus, it is supposed that there are unsaturated alcohol species present which were formed from HMF. From the spectrum, it is unlikely that the furan ring was opened, since this would require a stronger acid than malonic acid and water. Therefore, with the number of unsaturations present in the aromatic and alcohol region and the viscous appearance of the solid, it is assumed that some type of polymerization occurred that formed polar compounds.

Using dodecane as an internal standard the conversion was determined to be 100% as HMF was not present in the liquid phase. This was confirmed when the liquid

phase was analyzed via ^{1}H NMR, and there was no HMF present. This is seen in Figure 37.

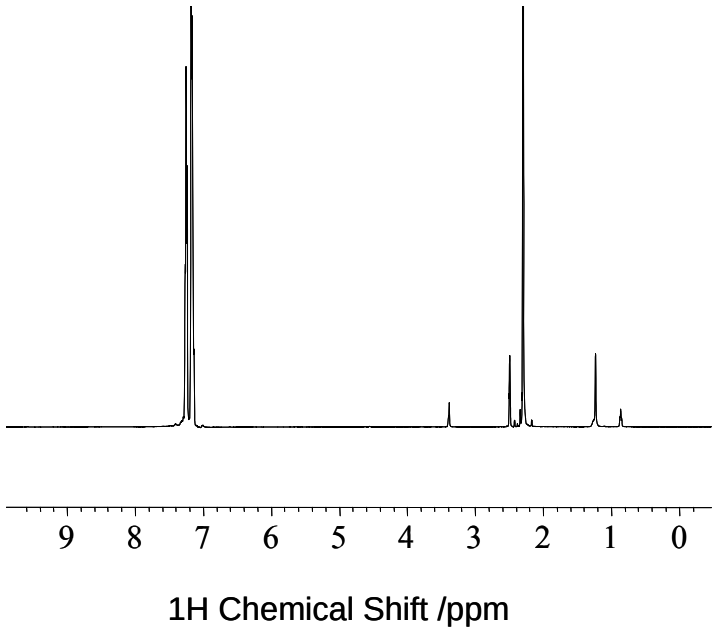


Figure 37: Liquid phase of Knoevenagel reaction using toluene

Chemical shifts at δ=1.3 and 0.8ppm are due to dodecane, but the signal at δ=3.3ppm could be due to malonic acid. These results show that toluene causes the formation of several compounds in the Knoevenagel reaction of HMF and malonic acid.

g) Ethyl ether

Using ethyl ether as solvent a white precipitate was identified after 5 hours, which gave the spectra Figure 38 when analyzed by ^{1}H NMR.

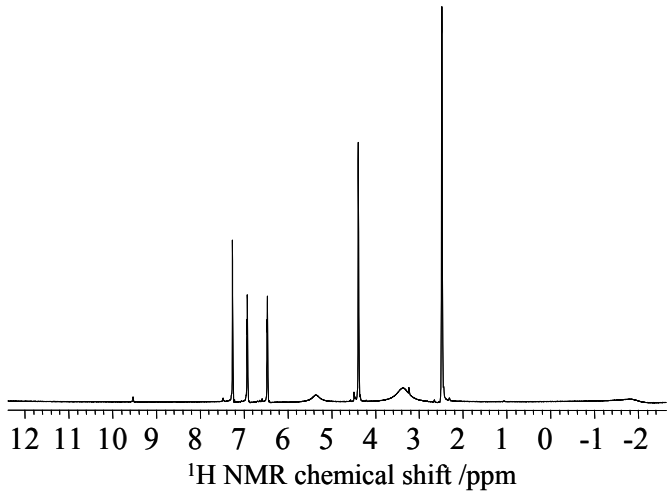


Figure 38: Precipitate from ethyl ether analyzed by ^{1}H NMR in DMSO-d_6

As was seen with ethyl acetate, there are traces of HMF present in the solid phase. However, most of the HMF is in the liquid phase and an overall conversion of 31% was obtained.

These experiments show that the choice of solvent can impact a product distribution between liquid and solid phases and solvents with a low di-electric constant allow for a precipitation of 2-((5-hydroxymethyl)furan-2-ylmethylene)malonic acid.

4.2-2: Effect of concentration of reactants on HMF conversion

Experiments were conducted with 10mmol of HMF, 10mmol malonic acid, 50mg ethylendiamine on poly(styrene) in 10ml THF (BHT) for 5 hours in a pressure tube. The results were 79% conversion with 99% selectivity, as opposed to 65% conversion with 2mmol HMF, 2mmol malonic acid and 10mg ethylendiamine on poly(styrene) under the same conditions. Furthermore, a solid precipitated out of the solution which was identified by ^{1}H NMR to be 2-((5-hydroxymethyl)furan-2-ylmethylene)malonic acid. This shows that at higher concentration, the solubility of the product reaches a limit and it

then falls out of solution. This is assumed to be due to a different chemistry than the precipitation seen for the other solvents e.g. ethyl acetate.

4.3: Effect of catalyst on levulinic acid conversion

The Knoevenagel reaction between levulinic acid would produce a tricarboxylic compound as shown in Figure 39.

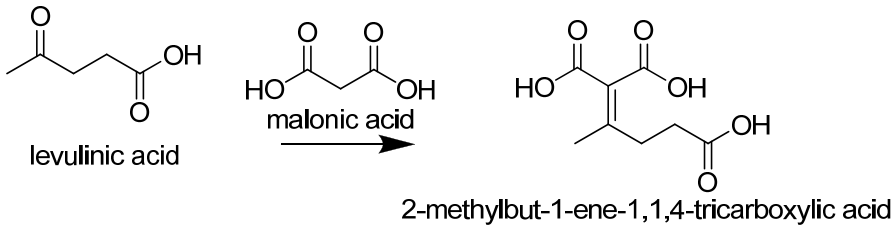


Figure 39: Knoevenagel reaction between levulinic acid and malonic acid

To achieve this goal, reactions were performed using 2mmol levulinic acid, 2mmol malonic acid, 10mg ethylenediamine on poly(styrene) in 10ml THF (BHT) at 80°C for 5 hours. The product obtained after removing the THF solvent by rota-evaporation was analyzed using ^{1}H NMR and ^{13}C NMR. The ^{13}C NMR spectrum is shown in Figure 40 of this product.

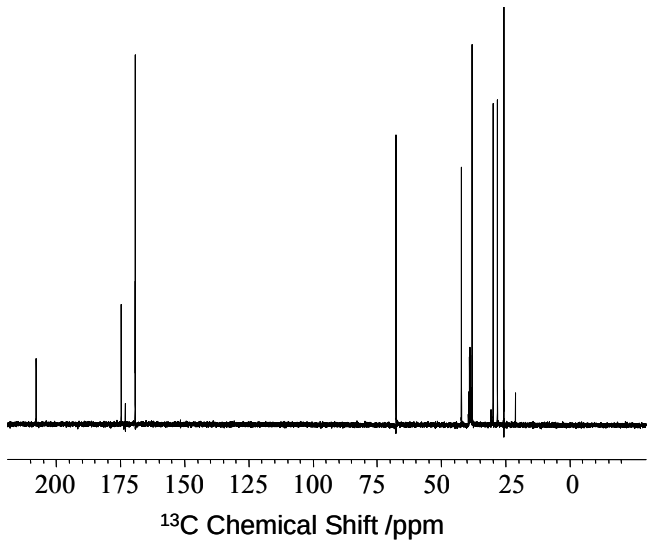


Figure 40: ^{13}C NMR of product from Knoevenagel reaction between levulinic acid and malonic acid in DMSO-d_6
Chemical Shifts /ppm (300MHz):
Levulinic acid: 207, 174, 38, 30, 28;
THF: 68, 26;
Malonic acid: 169, 42;

In ^{13}C NMR, the olefinic (carbon double bond) region of the spectrum lies in the range of 110-150ppm [92]. The absence of resonances in this region in Figure 40 indicates that olefinic compounds do not exist in the product mixture. Furthermore, the position of the resonances of the starting compounds (levulinic acid, malonic acid and THF) did not change. Therefore, the Knoevenagel reaction did not occur since the tricarboxylic product in Figure 39 has a carbon-carbon double bond.

The homogeneous ethylenediamine was then used since this catalyst performed better than the other catalysts used in this study. The homogeneous ethylenediamine was used in the same catalytic amounts as previous experiments for fufural and HMF (2µl), but on analyzing the product by ^{13}C NMR, a spectrum identical to Figure 40 was seen. Thus both homogeneous and heterogeneous ethylenediamine were unable to catalyze the Knoevenagel reaction between levulinic acid and malonic acid in the amounts used in this study.

A possible reason for the lack of reactivity was attributed to the fact that levulinic acid exists in its hemi-acetal form as shown in Figure 7, and thus the carbonyl group from the ketone in the straight form is not available for carbon-carbon bond formation. The lack of reactivity further indicates that the carbonyl group in the carboxylic acid end does not form a carbon-carbon bond with the enolate ion as carbonyls in aldehyes.

To determine whether the carboxy group had an effect on the reaction, ethyl levulinate was purchased and used. The Knoevenagel reaction would proceed according to Figure 41.

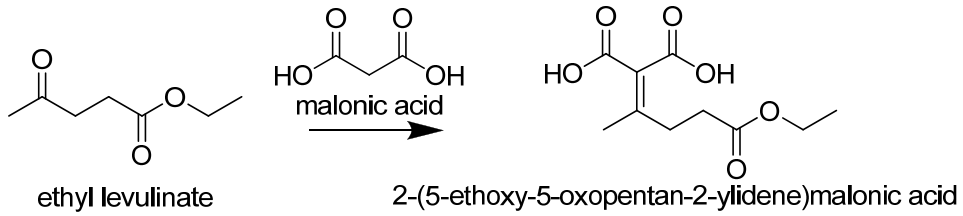


Figure 41: Knoevenagel reaction between ethyl levulinate and malonic acid

To determine whether the above reaction would proceed, reactions were performed with 2mmol ethyl levulinate, 2mmol malonic acid, 10mg ethylenediamine on poly(styrene) in 10ml THF (BHT) at 80°C for 5 hours. The ^{13}C NMR of the isolated product is shown in Figure 42.

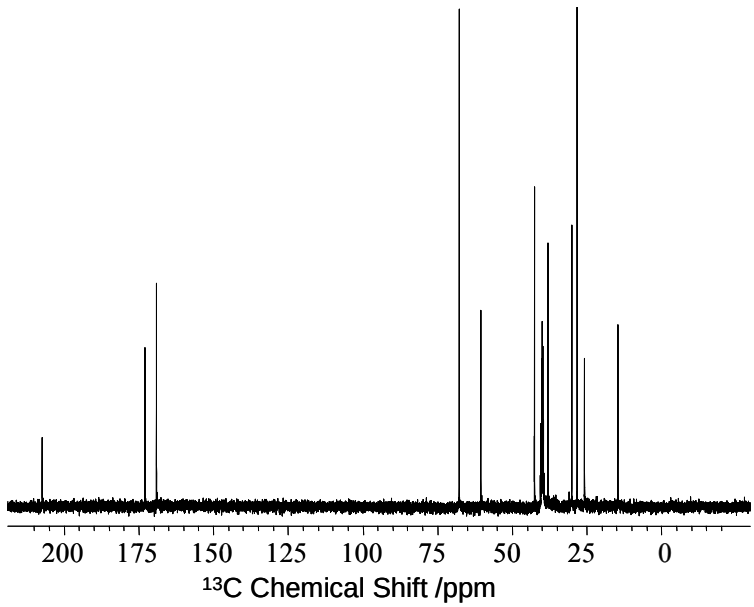


Figure 42: ^{13}C of product from Knoevenagel reaction of ethyl levulinate and malonic acid in DMSO-d_6
Chemical shifts (300MHz): Ethyl levulinate: 207.2, 172, 60.5, 37.9, 29.82, 28.09, 14.2; Malonic acid: 169, 60.4; THF: 67.6, 28.1

Examining Figure 42 shows that in this case as well, there were no resonances in the 110-150ppm region, and thus the Knoevenagel reaction did not occur. The homogeneous ethylenediamine was also utilized, but a spectrum identical to Figure 42 was seen on analyzing the product obtained.

Since the reactions with furfural and HMF worked with the ethylenediamine, it is safe to assume that the abstraction of the proton to create the enolate ion (Figure 9) is achieved in THF by ethylenediamine. Assuming that the same mechanism occurs for the Knoevenagel reaction between levulinic acid and malonic acid catalyzed by ethylenediamine, it is possible that the ketone group of levulinic acid is not reactive enough under these conditions with the enolate ion. In 1959, Stevens reported using levulinic acid and cyanoacetate derivatives in a Knovenagel condensation, employing Cope's method [80]. This method involves using glacial acetic acid as a co-solvent [80]. Using ammonium acetate (3.85g) as catalyst, benzene (50ml) as solvent, and acetic acid

(6g) with 0.5mol each of the levulinate derivate and cyanoacetic derivative, the reaction was carried out overnight (12 hours), and a Dean-Stark trap was used to remove water. Yields of 50-92% were obtained [80].

It has been noted in the literature that in general ketones are a less reactive species than aldehydes [53]. Nonetheless, it is possible for levulinic acid and ethyl levulinate to undergo the Knoevenagel reaction [80], but under the conditions of this study they did not.

4-4: Competition reactions between HMF and furfural

It is likely that in a bio-refinery that produces fuels from biomass would utilize furfural and HMF simultaneously. This could advantageously reduce the number of overall processing steps. With this in mind, reactions were performed to determine whether the malonic acid enolate ion would preferentially react with HMF than with furfural in an environment where there was a choice of both to form carbon-carbon bonds.

Experiments were performed with 2mmol of each aldehyde (HMF and furfural) and 2mmol malonic acid for 1 hour at 80°C in a 15ml pressure tube using 10mg of poly(styrene) supported ethylenediamine as catalyst (0.75mol% catalyst equivalent to aldehyde). The results are shown in Figure 43.

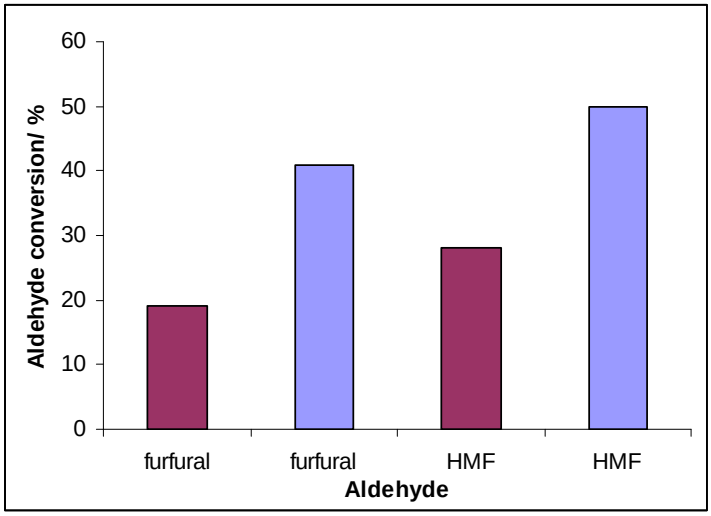


Figure 43: Competition & single reactions after 1h
Blue: 1 aldehyde present (non-competitive)
Violet: 2 aldehydes in the same reactor (competition runs)

The selectivities were 99-100% in all cases. Compared to the reactions where the aldehyde alone is present (HMF: 50% conversion after 1 hour; furfural: 40% conversion after 1 hour), the conversions are roughly half when they are in competition with each other (HMF: 29% after 1 hour; furfural 19% after 1 hour).

When the experiment was performed for 5 hours using the poly(styrene) supported ethylenediamine with 2mmol each of furfural, HMF and malonic acid, the final conversions were 30% for furfural and 33% for HMF. Using the homogeneous ethylenediamine as catalyst with 2mmol each of furfural, HMF and malonic acid, the conversions were roughly 50% for both furfural and HMF with selectivities of 99%. In this experiment all of the malonic acid was consumed. These results confirm earlier observations that the supported catalyst is not as effective as the homogeneous catalyst.

4.5: Analyses of the supported Ethylenediamine catalyst: recycle reactions and characterizations

To determine the recycle-ability of the ethylenediamine on poly(styrene) catalyst and possible reasons for catalyst deactivation, the catalyst from an experiment using 2mmol furfural and 2mmol malonic acid with 1.5mol% of ethylenediamine on poly(styrene) in 10ml THF performed in a 15ml pressure tube was reused. The product was analyzed by ^{1}H NMR and gave 49% conversion with 100% selectivity in the first experiment, and 0% conversion in its second use. The results from the HMF experiments are shown in Figure 44.

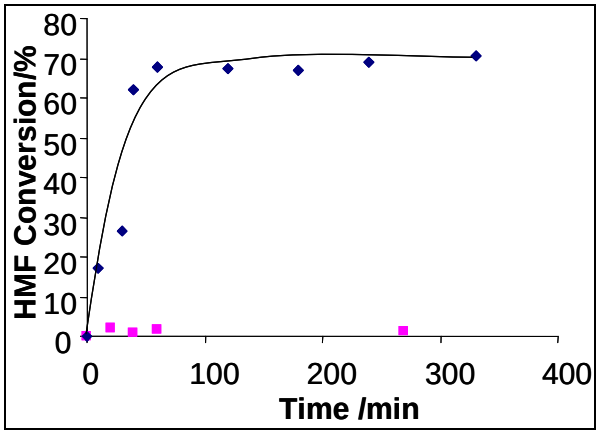


Figure 44: Catalyst re-use experiments
Legend:
Blue dots: First experiment
Pink dots: Catalyst reuse

Figure 44 shows that the conversion drops to 0% in a re-use experiment. This implies that the basic sites are unavailable in the recycled reaction for both HMF and furfural since there is no conversion in subsequent reactions. Since the unavailability of basic sites can be due to the amine sites being reacted in an irreversible manner on the catalyst surface, the surface of the catalyst was characterized by Infra-red radiation spectroscopy (IR).

To investigate this, a portion of the catalyst was removed before being recycled and was dried in an oven for 15 minutes at 105°C before being analyzed by IR. The IR spectra of the spent catalysts from separate HMF experiments and the IR of the unused (fresh) catalyst are given in Figure 45.

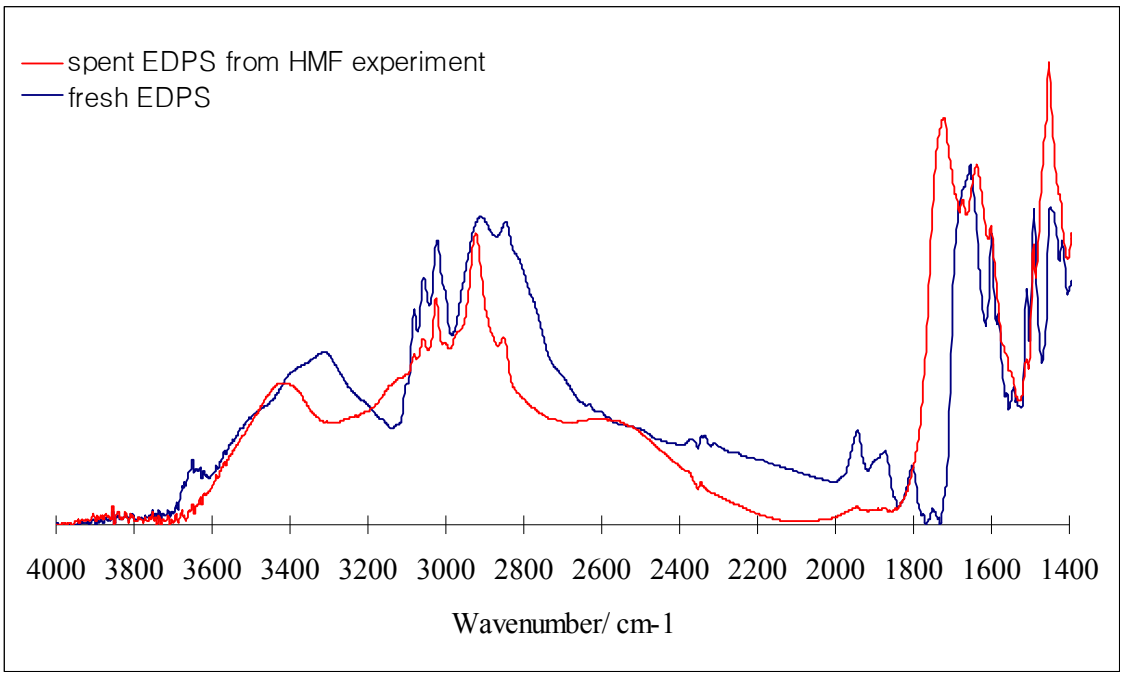


Figure 45: IR spectra of spent and fresh catalysts

In the region near 3100 cm^{-1}-3400 cm^{-1}, -OH and –NH stretching bands are observed and the N-H bending vibrations are also observed in the 1650-1580 cm^{-1} region [92]. However, the N-H stretching vibrations can overlap with physisorbed water (H_2O) on the amine surface (TGA analysis revealed that there was 1.6wt% physisorbed water on the surface of the ethylenediamine on polystyrene) [54]. Also, the C=O stretching vibrations of the Amide I Band absorbs in the region of 1650 cm^{-1}. Vibrations in the 2900cm^{-1} are due to aliphatic C-H stretches, while aromatic ring vibrations occur near 1600cm^{-1} [92].

Figure 45 shows that the bands at 3400-3500 cm^{-1} are reduced from the fresh and the spent catalysts. This implies that the amine groups are disappearing, possibly to a reaction with the malonic acid. Also, there are broader peaks between 1700-1750cm^{-1}, which is in the approximate region for carbonyl groups. These results imply that the catalyst is deactivated by a carbonyl compound present on the catalyst surface, thus blocking access of other molecules to the amine sites. The role of deactivation by a permanent site blockage could explain why the reaction does not proceed for HMF and furfural in this study.

However, the since the reaction goes to completion with the homogeneous ethylenediamine and N-propylethylenediamine, it is unlikely that the amine groups are deactivated by reacting with species in solution such as the aldehyde group or the carboxylic acid group. Thus reasons for deactivation are assumed to be due to either:

1. The support itself permanently blocks access to the active amine sites or
2. A species in solution blocks access to the site by reacting with the amine groups (e.g. malonic acid).

4.6: Hydrogenation of 2-((5-hydroxymethyl)furan-2-ylmethylene)malonic acid using Ru/Al_2O_3

As 5 wt% Ru/Al_2O_3 was shown to be an effective catalyst for the hydrodeoxygenation (HDO) of lactic acid into propylene glycol [51], this catalyst was used in initial HDO experiments. Approximately 50mg of 2-((5-hydroxymethyl)furan-2-ylmethylene) malonic acid was dissolved in 25ml of water and this was charged into the reactor. This was obtained by performing a reaction using 1.5mol% of homogeneous ethylenediamine with 2mmol HMF and malonic acid in THF at 80°C for 5 hours. The

product was essentially 90% pure with the remaining 10% consisting of THF and malonic acid present.

A five weight percent (5wt%) Ru/Al_2O_3 (catalyst) was obtained from SigmaAldrich, and 125mg of this catalyst was reduced at 450psi H_2 at 373K in a 300ml Parr reactor for 2 hours (C in Figure 12). The hydrogenation reaction was then performed for 5 hours at 450 psi H_2 at 373 K. After the reaction was completed, the catalyst was filtered from the solution and the water was removed by overnight cooling at 333K. The mixture before hydrogenation is shown in Figure 46, while the ^1H NMR spectra of the solid residue after hydrogenation in DMSO-d_6 is shown in Figure 47.

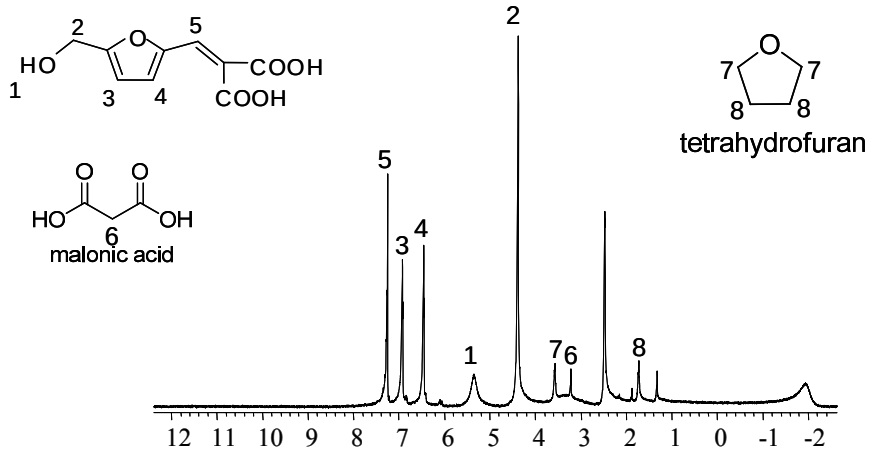


Figure 46: ^1H NMR of the material before hydrogenation

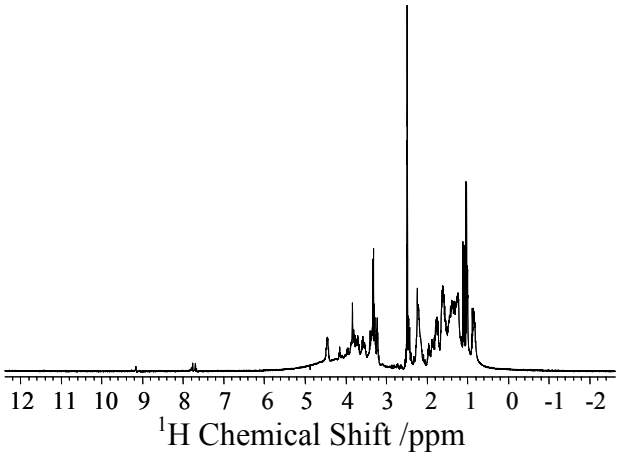


Figure 47: ^1H NMR of preliminary HDO experiment

Figure 47 shows that resonances that were previously in the aromatic region (δ=6 to δ=9ppm) have been removed and the aliphatic region (δ=0 to δ=2ppm) contains several resonances [92]. The resonance at δ=4.5ppm is a hydroxyl group, which indicates that aliphatic alcohols are present. It is likely that the presence of alumina contributed acidic sites, which were used to open the furan ring. Also, the number of resonances in the aliphatic region indicates that several fragments were formed in the HDO process. While in this preliminary experiment the mass of catalyst used could be considered excessive, the amount of catalyst was used in an exploratory manner to determine the product distribution.

CHAPTER 5

CONCLUSIONS

In this study, the Knoevenagel reaction was applied to furfural, HMF and levulinic acid with malonic acid to produce unsaturated di-acids as the primary products.

With HMF and furfural, it was shown that the reaction could be performed in solvents such as THF, water, ethanol, ethyl ether, and ethyl acetate. It was identified that the HMF Knoevenagel product precipitated out of the ethyl acetate ethyl ether and THF in high concentrations, while the furfural product precipitated out of toluene. These consequences are favorable for product removal.

Measured conversions in THF after 5 hours with a range of amines showed that homoegeneous catalysts performed better than supported catalysts. In particular, supported ethylenediamine showed that a higher conversion for HMF than furfural. Competition reactions between these two compounds also resulted in higher conversion using both poly(styrene) supported ethylenediamine and homogeneous ethylenediamine. In all experiments performed, selectivity for the di-acid was high (97-99%) and thus decarboxylation reactions did not occur significantly.

Levulinic acid and ethyl levulinate did not give any conversion under the conditions used in this study. Possible reasons for this are unclear, but results from the literature suggest that the solvent chosen plays a role in the reaction.

A hydrogenation experiment was performed on the HMF product using 5wt% Ru/Al_2O_3 under hydrogen. Several compounds with resonances in the alcohol substituted

aliphatic region were produced. These results suggest that it is possible to convert the Knoevenagel product (di carboxylic acids) into a compound with a lower oxygen content.

CHAPTER 6

RECOMMENDATIONS

There are several possible improvements that can be made in furthering this study. Improvements are possible in the catalyst for the reaction and its recycle ability. Currently, the supported catalyst used most frequently in this study (ethylenediamine on poly(styrene)) loses its activity after 1 cycle and performs less effectively than the homogeneous catalysts for both HMF and furfural. Furthermore, bi-functional catalysts that contain both basic sites for the Knoevenagel reaction and metal sites for the hydrogenation would allow for reactions in 1 pot, which would reduce overall steps and costs. However, in the design of such catalysts, it would be necessary to ensure that the metal sites do not leach from the catalyst during Knoevenagel or hydrogenation reactions.

In terms of the solvents used for the reaction, opportunities exist in the use of ethyl acetate, ethyl ether and toluene since the Knoevenagel products precipitate out of these solutions depending on the product involved. Since the ideal solvent would be easily separated from the product mixture and re-used, the cost of the solvent can be spread over the process. Thus research is needed to find such a solvent.

Furthermore, the quantity and availability of the raw materials (HMF, furfural, levulinic acid) would have to be determined for this process to be successfully applied on a large scale. On such a scale, the economics would have to justify an initial investment. Thus, to determine its overall feasibility, the economics of the entire process would have to be measured from a raw material to finished product. Figure 48 shows a potential path to product alkanes utilizing the Knovenagel reaction starting from glucose.

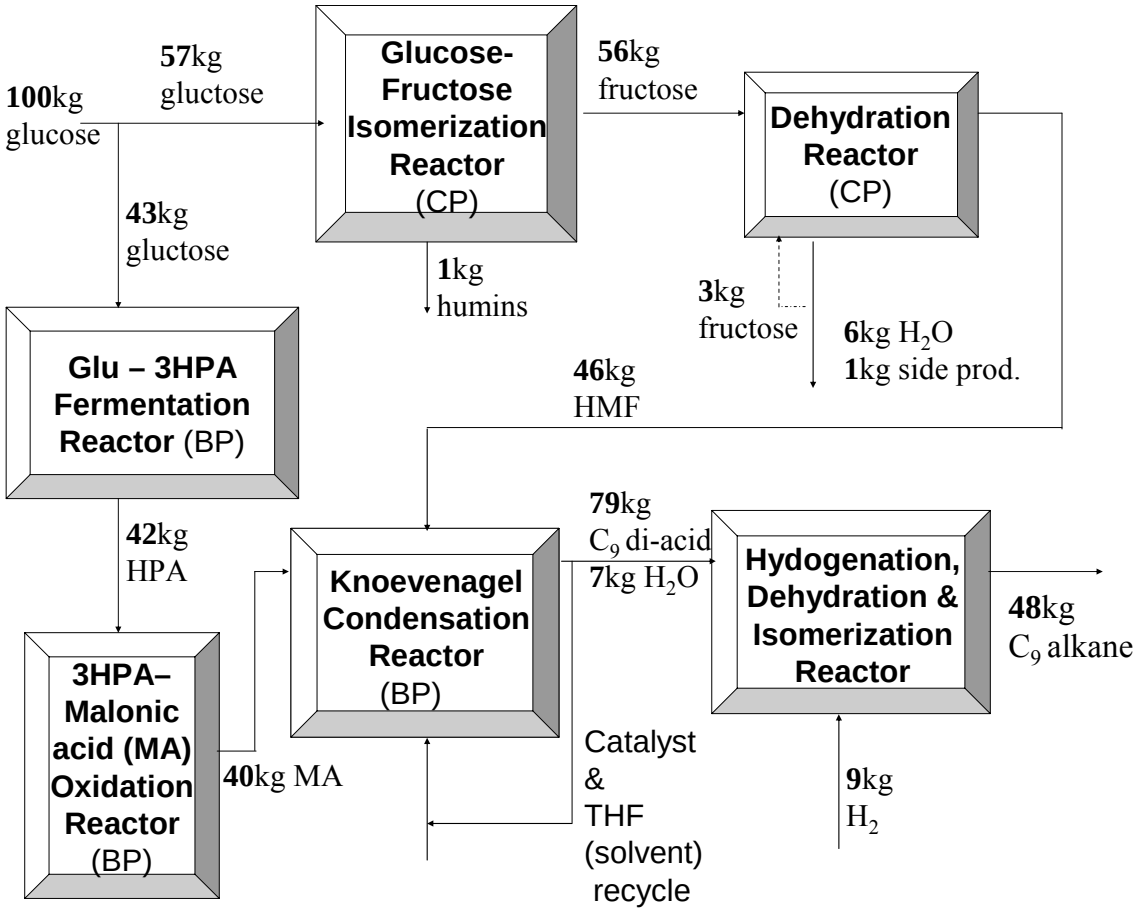


Figure 48: Process flow diagram to produce alkanes from glucose utilizing the Knoevenagel reaction

In general the glucose to fructose isomerization step is necessary with current technology as higher yields of HMF are obtainable from fructose than glucose [32]. The process is carried out utilizing the enzyme glucose isomeraze in a continuous process. Dehydration of fructose to HMF can be achieved in 90% conversion with 80% selectivity [93]. Glucose conversion to 3-hydroxypropionic acid is being researched by Cargill Incorporated with a patented technology [94], and conversion of 3HPA to malonic acid are reported in the literature with yields higher than 90% [48, 49]. Ninety-seven percent (97%) and 95% conversion with 100% selectivity were assumed for these two steps respectively in Figure 49.

The results from this study show that the Knoevenagel product from HMF, 2-((5-hydroxymethyl)furan-2-ylmethylene)malonic acid, can be produced in high yield and selectivity (both 100%). Once produced, the hydrogenation and isomerization would follow Equation (i) shown below to remove oxygen from the Knoevenagel product:

$$C_9H_8O_6 + 12H_2 \rightarrow C_9H_{20} + 6H_2O \qquad \ldots(i)$$

Thus with 0.37kmol of 2-((5-hydroxymethyl)furan-2-ylmethylene)malonic acid (79kg/212kg $kmol^{-1}$), the maximum amount of n-alkane that can be produced is 48kg, for an overall process yield of 48 wt%. However, depending on the amount of oxygen allowed in the final product (nonane being the oxygen-free product), the final mass of the product can be higher.

The overall energy efficiency for the production of alkanes (nonane) from glucose utilizing the Knoevenagel reaction can be determined using the following equations that summarize processes in Figure 48:

1) Dehydration of glucose to produce HMF:

$$C_6H_{12}O_6 \rightarrow C_6H_6O_3 + H_2 \ldots(ii)$$

2) Fermentation of glucose to produce 3-hydroxypropionic acid:

$$\frac{1}{2}C_6H_{12}O_6 \rightarrow C_3H_6O_3 \ldots. (iii)$$

3) Oxidation of 3-hydroxypropionic acid to produce malonic acid:

$$O_2 + C_3H_6O_3 \rightarrow C_3H_4O_4 + H_2O \ldots (iv)$$

4) Knoevenagel reaction between malonic acid and HMF to produce 2-((5-hydroxymethyl)furan-2-ylmethylene)malonic acid:

$$C_3H_4O_4 + C_6H_6O_3 \rightarrow C_9H_8O_6 + H_2O \ldots (v)$$

5) Production of hydrogen by aqueous-phase reforming of glucose [95]:

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 12H_2 \ldots \text{(vi)}$$

6) Hydrogenation of 2-((5-hydroxymethyl)furan-2-ylmethylene)malonic acid:

$$C_9H_8O_6 + 12H_2 \rightarrow C_9H_{20} + 6H_2O \ldots \text{(vii)}$$

These equations (ii-vii) combine to give the overall equation:

$$\frac{5}{2}C_6H_{12}O_6 + O_2 \rightarrow C_9H_{20} + 5H_2O + 6CO_2 \ldots \text{(vii)}$$

The enthalpy of combustion for glucose is calculated to be 2803kJ/mol, and the enthalpy of combustion of nonane is calculated to be 6125kJ/mol (Appendix). Taking a basis as 1 ton of glucose, and using the stoichiometry in Equation vii, the nonane is determined to contain 87% of the energy of the glucose, with a heating value of approximately 13,607,000 kJ/$ton_{glucose}$.

Throughout this analysis, yields and selectivity followed best case scenarios. Furthermore, hydrogen that was used in the process was assumed to be provided by the aqueous phase hydrolysis of glucose. However, in a real process, yields would be lower due to side reactions of products and losses in efficiency. Nonetheless, the above analysis highlights promising possibilities in mass yields and energy content of a fuel (nonane) derivable from biomass.

APPENDIX A

1) Percent molar concentration of amines used in experiments

Using 3-aminopropyl on silica as an example (loading: 1mmol N/g)

30mg of this catalyst contains = $\frac{30mg}{} * \frac{1mmolN}{g} * \frac{1g}{1000mg} * \frac{1mol}{1000mmol}$ = 3x10^{-5} mol N

No. mols aldehyde = 2x10^{-3}mols

% molar concentration of amines = $\frac{0.00003}{0.002 + 0.00003} * 100 = 1.478\% \sim 1.5\%$

2) Standard heat of combustion calculations

Using heat of formation data, the following equations (ix and x) can be used to estimate the standard heat of combustion of a compound containing carbon, hydrogen and oxygen [82]

$$C_aH_bO_c + (a + 0.25b - 0.5c)\ O_2 \rightarrow a\ CO_2 + 0.5b\ H_2O \quad \ldots(ix)$$

$$\Delta H^o_c = 393.51a + 142.915b + \Delta H_f\ (C_aH_bO_c) \quad \ldots(x)$$

Compound	ΔH_f (kJ/mol) [82]	ΔH^o_c (kJ/mol)
α-D-glucose	-1273.3	2802.7
n-nonane	-274.7	6125.2
CO_2 (g)	-393.5	-
H_2O (l)	-285.8	-

Using the stoichiometry of Equation (vii), and assuming 1 ton of glucose as a basis,

No. mols glucose = $\frac{1ton}{} * \frac{1000kg}{1ton} * \frac{1000mol}{1kmol} * \frac{1kmol_{glucose}}{180kg}$ = 5.6x10^{3}mols

No. mols nonane= $\frac{1mol_{nonane}}{2.5mol_{glucose}} * 5.6x10^3$mols= 2.2x10^{3}mols

Energy released by combustion of 5.6x10^{3}mols glucose = -15592222.22 kJ/mol

Energy released by combustion of 2.2x10^{3}mols nonane = -13606666.67 kJ/mol

% energy contained in nonane from glucose = $\frac{-13606666.67}{-15592222.22}$ = 87.3%

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