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Catalytic Conversion of Fructose, Glucose and Industrial Grade Sugar Syrups to 5-Hydroxymethylfurfural, A Platform for Fuels and Chemicals

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Abstract

HydroxyMethylFurfural (HMF) as a versatile and poly-functional compound derived from dehydration of biomass has attracted increasing attentions in research over the past decades. HMF is an important intermediate and platform chemical, which can be converted into different useful chemicals as well as the promising biofuels. It can be obtained from acid-catalyzed dehydration of different C_6-based carbohydrates such as glucose, fructose, sucrose and cellulose.

In this thesis, a cost-effective process for catalytic conversion of simple sugars (particularly glucose and fructose) and industrial grade sugar syrups to HMF was studied in a novel biphasic continuous-flow tubular reactor using inexpensive heterogeneous solid catalysts and biphasic media (aqueous/organic). Commercial and synthesized heterogeneous catalysts were used for the catalytic experiments and their activities in terms of conversion, selectivity and yield were compared. It is assumed that catalytic conversion of glucose to HMF involves two-step reaction pathway of glucose isomerization to fructose and subsequent fructose dehydration to HMF. Thus, the experimental approach for this research was to first isomerize glucose to fructose using heterogeneous solid base catalysts and then dehydrate fructose to HMF using heterogeneous solid acid catalysts. Thereafter, continuous single-step conversion of glucose and industrial grade sugar syrups derived from corn and wood to HMF was investigated. In each section, fresh catalysts were characterized comprehensively and the stability of some selected catalysts and feasibility of catalyst recycling were examined. The effects of different experimental conditions including reaction temperature, feeding flow rate, initial feedstock concentration, catalyst loading, presence of extracting organic solvent and phase transfer catalyst were also studied. At the best operating conditions, the maximum fructose yield of 25% was achieved from isomerization of glucose over magnesium oxide catalyst and maximum HMF yields of 60%, 45% and 53% were obtained from dehydration of fructose (over Amberlyst 36 catalyst), glucose (over niobium phosphate catalyst) and HFCS-90 (over niobium phosphate catalyst), respectively. The deactivation mechanism of some selected catalysts was also investigated by analysing the used catalysts and the insoluble humins produced during the reaction as the main by-product responsible for the catalyst deactivation. The kinetics of glucose dehydration reaction over niobium phosphate catalyst was also studied.

Keywords:

5-Hydroxymethylfurfural (HMF), Glucose, Fructose, Isomerization, Dehydration, Biphasic continuous-flow tubular reactor, Heterogeneous solid catalyst, Niobium phosphate, Amberlyst 36, Hydrotalcite, Magnesium oxide, Catalyst characterization, Catalyst deactivation, Catalyst stability, Catalyst reusability, Catalyst recycling, Catalyst regeneration, High fructose corn syrup (HFCS), Glucose corn syrup (GCS), TMP-Bio Sugar, Glucose dehydration reaction kinetics, Humins characterizations

Co-Authorship Statement

Chapter 3: Catalytic Isomerization of Glucose to Fructose using Heterogeneous Solid Base Catalysts in a Continuous-Flow Tubular Reactor: Catalyst Screening Study

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The experimental work was conducted by Sadra Souzanchi under the supervision of Prof. Charles (Chunbao) Xu and Prof. Zhongchao Tan and the guidance of Dr. Zhongshun Yuan. Data analysis, results interpretation and writing were performed by Sadra Souzanchi assisted by Laleh Nazari and Tirumala Kasanneni. The paper was reviewed and revised by Prof. Charles Xu and Prof. Zhongchao Tan and the manuscript has been submitted to "*Catalysis Today*" journal for publication.

Chapter 4: Catalytic Isomerization of Glucose to Fructose using Activated Hydrotalcite Catalyst in a Continuous-Flow Tubular Reactor: Effects of Reaction Conditions

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Chapter 5: Catalytic Dehydration of Fructose to 5-HMF using Heterogeneous Solid Acid Catalysts in a Biphasic Continuous-Flow Tubular Reactor

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The experimental work was conducted by Sadra Souzanchi under the supervision of Prof. Charles (Chunbao) Xu and Prof. Zhongchao Tan and the guidance of Dr. Zhongshun Yuan.

Data analysis, results interpretation and writing were performed by Sadra Souzanchi assisted by Laleh Nazari and Tirumala Kasanneni. The paper was reviewed and revised by Prof. Charles Xu and Prof. Zhongchao Tan and the manuscript is to be submitted for publication.

Chapter 6: Catalytic Dehydration of Glucose to 5-HMF using Heterogeneous Solid Acid Catalysts in a Biphasic Continuous-Flow Tubular Reactor

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Chapter 7: HMF Production from Industrial Grade Sugar Syrups Derived from Corn and Wood using Niobium Phosphate Catalyst in a Biphasic Continuous-Flow Tubular Reactor

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The experimental work was conducted by Sadra Souzanchi under the supervision of Prof. Charles (Chunbao) Xu and Prof. Zhongchao Tan and the guidance of Dr. Zhongshun Yuan. Data analysis, results interpretation and writing were performed by Sadra Souzanchi assisted by Laleh Nazari and Tirumala Kasanneni. The paper was reviewed and revised by Prof. Charles Xu and Prof. Zhongchao Tan and the manuscript is to be submitted for publication.

Dedication

To my beloved wife, Laleh, for her love, devotion and for being there for me throughout the entire of this journey

&

To my loving parents, Ali and Shahin, for their endless love, encouragement and support

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Though only my name appears on the cover of this dissertation, it would not have been possible to publish this work without the help of so many people who have contributed to its body of work. I owe my gratitude to all those people who have made this dissertation possible and because of whom my graduate experience has been one that I will cherish forever.

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Sadra Souzanchi
Western University
August 2016

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List of Abbreviations and Symbols

A/O	Aqueous to Organic Phase Ratio
ACN	Acetonitrile
AHG	1,6-Anhydroglucose
Amb. 15	Amberlyst 15
Amb. 36	Amberlyst 36
Amb. A21	Amberlyst A21
B/L	Brønsted to Lewis Acid Sites Ratio
BET	Brunauer-Emmett-Teller
CaP	Calcium Phosphate Dibasic
CHNS	Carbon, Hydrogen, Nitrogen and Sulfur Elemental Analysis
CMF	5-Chloromethylfurfural
CrP	Chromic Phosphate
CSTR	Continuous Stirred Tank Reactor
DCM	Dichloromethan
DMF	2,5-Dimethylfuran
DMA	Dimethylacetamide
DMF	Dimethylformamide
DMSO	Dimethylsulphoxide
DTG	Derivative Thermogravimetric
EA	Ethyl Acetate
FC	Fixed Carbon
FDCA	2,5-Furandicarboxylic Acid
FT-IR	Fourier Transform Infrared
GCS	Glucose Corn Syrup

H/C	Molar Ratio of Hydrogen to Carbon
HCW	Hot Compressed Water
HFCS	High Fructose Corn Syrup
HMF (5-HMF)	5-(hydroxymethyl)-2-furaldehyde (5-Hydroxymethylfurfural)
HPLC	High Performance Liquid Chromatography
HT	Hydrotalcite
HT-C	Calcined Hydrotalcite
HT-C-R	Calcined-Rehydrated Hydrotalcite
HT MG30	SASOL PURAL MG30 Hydrotalcite
HT MG30/K_2CO_3	SASOL PURAL MG30/K_2CO_3 Hydrotalcite
IL	Ionic Liquid
LA	Levulinic Acid
MIBK	Methyl Isobutyl Ketone (4-Methyl-2-pentanone)
NbA	Niobic Acid (Niobium Pentoxide Hydrate)
NbP	Niobium Phosphate Hydrate
NbP-syn	Synthetized Niobium Phosphate
NbS-syn	Synthetized Niobium Sulfate
O/C	Molar Ratio of Hydrogen to Carbon
PFR	Plug Flow Reactor
PSD	Pore Size Distribution
PTC	Phase Transfer Catalyst
Py-FTIR	Pyridine adsorbed FT-IR
RI	Refractive Index
TCD	Thermal Conductivity Detector
TEA	Triethylamine
TEAC	Tetraethyl Ammonium Chloride

TGA	Thermogravimetric Analysis
THF	Tetrahydrofuran
TMP	Thermomechanical Pulping
TOS	Time On Stream
TPD	Temperature Programmed Desorption
UV	Ultraviolet
VM	Volatile Matter
WHSV	Wight Hourly Space Velocity
XRD	X-Ray Diffraction

Chapter 1

1 General Introduction

1.1 Background

The development of economically viable processes for the production of renewable fuels and materials has become one of the most important challenges for recent research due to serious environmental and economic issues related to our dependence on fossil fuels for energy and chemicals production.[1,2] As a result, biomass has attracted intensive attentions and more researchers focused on using biomass as a renewable and sustainable feedstock due to its globally abundance, eco-friendly and carbon-neutral nature.[3–6] Biomass, which consists of carbohydrates, lignin, fatty acids, lipids, proteins and others, is a promising feedstock for not only sustainable production of biofuels, but also a wide variety of chemicals and materials with properties similar to, or even better than those of petroleum-based products.[4] One of the major obstacles in the application of carbohydrates as a feedstock for the production of fuels and chemicals is the high amount of oxygen content in their molecular structure.

There are three main methods to reduce the oxygen content of hydrocarbons. The first is the removal of highly oxidized carbon molecules as CO_2, formaldehyde and formic acid (e.g., fermentative conversion of carbohydrates), the second is hydrogenolysis (i.e., removal of oxygen as a water molecule by adding hydrogen), and the third is dehydration (i.e., removal of oxygen by extracting water from the carbohydrate molecule).[7]

Glucose is one of the main building blocks of biomass, particularly cellulose and starch, which could be biologically converted to ethanol (by removing CO_2); however, this process is not efficient with regards to energy and carbon utilization efficiency. In addition, ethanol is characterized with low energy density, high volatility and tendency to absorb moisture from the air.[8] Therefore, other processes are developing to efficiently convert abundant resources of biomass into higher energy content biofuels. Among those technologies, much of the current efforts have been directed toward dehydration of carbohydrates to furan derivatives as intermediates for bulk production of biofuels and chemicals.[9,10]

Recently, many research efforts have been devoted toward the synthesis and production of 5-hydroxymethyl-2-furaldehyde or 5-hydroxymethylfurfural (5-HMF, referred to as "HMF" hereafter), which is one of the most important furan derivative compounds. Some physical and chemical properties of HMF are presented in Table 1.1.

Table 1.1: Physical and chemical properties of HMF

IUPAC Name	5-(hydroxymethyl)-2-furaldehyde
Chemical Formula	$C_6H_6O_3$
CAS No.	67-47-0
Physical State	Crystal Solid
Color/Appearance	Light Yellow (Tan)
Molar Mass	126.11 g/mol
Density	1.243 g/cm^3 at 25 ^{o}C
Melting Point	28-34 ^{o}C
Boiling Point	114-116 ^{o}C at 1 mmHg
Flash Point	79 ^{o}C - Closed Cup

HMF originates from hexoses by losing three molecules of water in an acid catalyzed reaction [11] and it is an important precursor and intermediate platform chemical that can be further converted into fuels and various valuable chemicals. Figure 1.1 shows some important molecules which can be formed through HMF. HMF could be further converted to 2,5-furandicarboxylic acid (FDCA), 2,5-dimethylfuran (DMF) and levulinic acid (LA), through specific catalytic transformation [12,13], which are considered to be highly useful intermediates for production of a variety of polymers and plastics.[3,12,13] It is also suggested that the DMF derived from HMF is a promising biofuel with a higher energy density and boiling point than ethanol.[3]

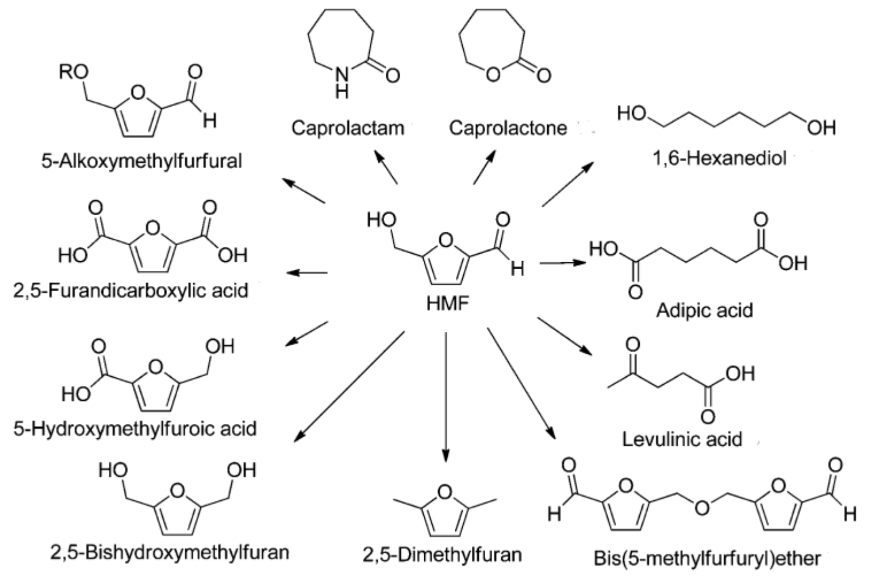

Figure 1.1: HMF as a platform for production of biomass-based fuels and chemicals, reprinted with permission from Ref. [7] Copyright (2013) American Chemical Society

HMF is also present in our diets, which are processed in bakery, dairy, honey and juice when a food consisting carbohydrates (particularly sugars) is heated during the process or in prolonged storage. It is formed as an intermediate of caramelization and through Millard reaction. Millard reaction occurs between the carbonyl groups of sugars and the amino groups of amino acids at temperatures above 50 ºC and acidic condition (pH 4-7); while caramelization is the oxidation of sugars and generally takes place at higher temperatures (>120 ºC) in the presence of little water.[14,15]

Synthesis of HMF was first reported in 1895 by Dull et al. by heating inulin in an oxalic acid solution, and contemporaneously Kiermayer suggested a similar process for HMF synthesis by using sugar cane.[7,16] In recent years, considerable efforts have been made on the transformation of carbohydrates into HMF.[9,10,13,17–23] HMF is mainly synthesized through the dehydration of C_6 monosaccharides (e.g., glucose and fructose) by losing three molecules of water. Disaccharides (e.g., sucrose and cellobiose) and polysaccharides (e.g., cellulose and starch) can also be used as feedstock for HMF production necessitating an initial step of hydrolysis for depolymerization to monosaccharides.

According to the literature, the mechanistic pathways of hexose dehydration to HMF can be divided into two general groups: one group presumes that the reactions proceed through acyclic intermediates and the other assumes cyclic intermediates.[24–28] Other studies propose that glucose is transformed to fructose through an acyclic mechanism or an enediol intermediate, but could be transformed to HMF in two pathways of either cyclic or acyclic routes.[28] Antal et al. and Newth suggested that fructose was dehydrated to HMF via cyclic intermediates [28–30] and Zhao et al. proposed that for conversion of glucose to HMF, metal halide catalysts promoted glucose isomerization to fructose by acyclic intermediate.[30] Guan et al. studied the conversion of glucose to HMF by metal chlorides as catalysts and proposed a two-step process of glucose isomerization to fructose and subsequent fructose dehydration to HMF in the catalytic cycle.[28,31] Figure 1.2 shows the reaction pathway for the proposed two-step process of HMF production from glucose. It has been reported that the first reaction (glucose isomerization to fructose) could be catalyzed by either base catalysts or Lewis acid catalysts, while the second reaction (fructose dehydration to HMF) by acid catalysts (Brønsted acid sites) and this poses a challenge in the synthesis of HMF from glucose.[5,32]

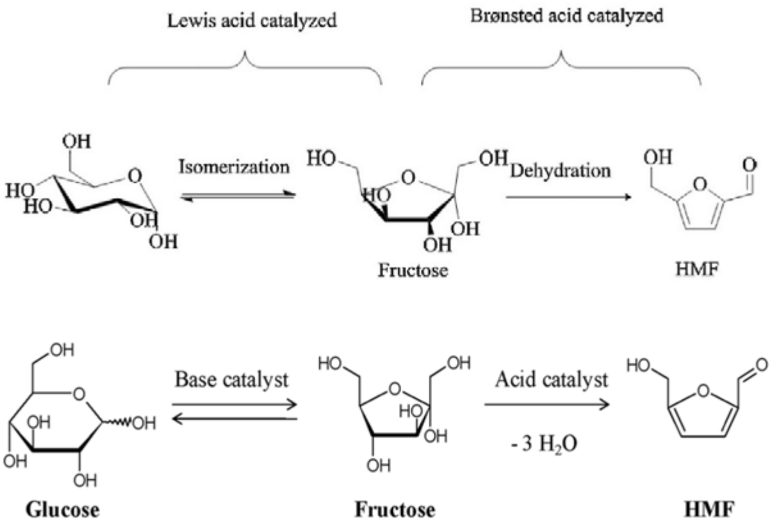

Figure 1.2: Two-step reaction pathways for glucose catalytic conversion to HMF, reprinted from Ref. [5] Copyright (2009) The Royal Society of Chemistry and Ref. [33] Copyright (2015) Elsevier

An important issue in the production of HMF from dehydration of sugars is the by-products produced through the variety of side reactions. It has been reported that at high temperatures and in the presence of water, feedstock (sugar), intermediates and final product (HMF) could undergo decomposition, rehydration, dehydration, condensation and polymerization reactions resulting in undesired by-products such as levulinic and formic acids (through rehydration of HMF) as well as oligomeric humins (through condensation and self-polymerization of feedstock, intermediates and product).[5,34] Figure 1.3 shows a reaction scheme of glucose conversion to HMF including potential side reactions and by products. It shows that the dehydration of sugars to produce HMF is complex and the main challenge in this process is to avoid the production of a variety of undesirable by-products in order to obtain a high HMF selectivity and yield. Thus, selection of an efficient and inexpensive catalyst as well as optimum operating conditions (e.g., reaction temperature, reaction time, feed concentration, catalyst loading) are essential to control the undesirable reactions and to improve the reaction kinetics.

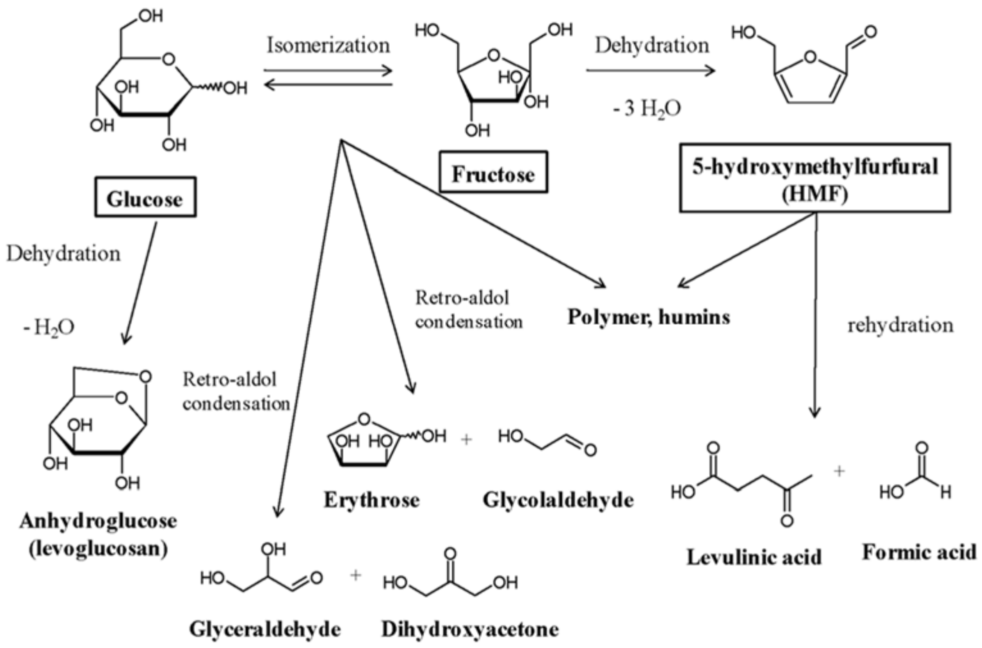

Figure 1.3: A reaction scheme for glucose conversion to HMF and potential side reactions and by-products, reprinted from Ref. [5] Copyright (2009) The Royal Society of Chemistry

1.2 Problem Statement and Research Objectives

Although HMF, its synthesis process and broad applications have been known for many years, the commercial and industrial production of HMF has not been fully developed yet to obtain furan type intermediate compounds on a large scale for the production of biofuels and chemicals. This is due to some barriers such as the difficulty of achieving a highly selective process with a high yield of final product, and cost-effective method for product isolation as well as the feasibility of operating the process in a continuous-flow reactor. That is why in the recent publications HMF has been named as "Sleeping Giant"!

Therefore, the main goal of this PhD project was to develop a cost-effective continuous-flow process for production of HMF from simple sugars (particularly glucose and fructose) and industrial grade sugar syrups with high selectivity and isolated yield in a biphasic (aqueous/organic) media using inexpensive heterogeneous catalyst. Successful accomplishment of this mission will simplify the route toward bulk production of HMF in a large industrial scale.

1.3 Approaches and Methodology

Considering and assuming the proposed two-step reaction pathway theory for the catalytic conversion of glucose to HMF, the experimental approach for this research was to conduct this process in two separate steps: First glucose isomerization to fructose using heterogeneous solid base catalysts (Chapters 3 and 4) and then fructose dehydration to HMF using heterogeneous solid acid catalysts (Chapter 5). Thereafter, continuous single-step conversion of glucose (Chapter 6) and industrial grade sugar syrups derived from corn and wood (Chapter 7) to HMF was investigated using the best catalysts in the previous studies.

Catalytic dehydration of simple sugars (particularly glucose and fructose) to HMF was performed in a novel biphasic continuous-flow tubular reactor (real photo is presented in Figure 1.4). The lab-scale reactor setup was devised and constructed in-house for testing different heterogeneous solid catalysts as a fixed bed within the tubular reactor for conversion of sugars into HMF. The particle size of the catalysts (d_p) and internal diameter of the tubular reactor (D) were in a suitable range ($6<D/d_p<30$) to avoid wall effects, high pressure drop and channeling flow of the fluid along the fixed-bed reactor. Pure glucose or fructose (as model compounds) solutions in water as well as diluted industrial grade sugar syrups derived from corn and wood were used as the feedstocks.

The details of the research approaches and methods as well as schematic diagram of the reactor setup and experimental procedures will be given in the corresponding subsequent chapters (Chapters 3 and 5). It is worth mentioning that the configuration of the continuous-flow reactor setup used for isomerization reactions of glucose to fructose (Chapters 3 and 4), which was carried out in a single aqueous phase medium, is slightly different and is presented and explained in the corresponding chapter (Chapter 3).

Figure 1.4: Photo of the biphasic continuous-flow tubular reactor

The relationship between feedstock concentration, feeding flow rate and catalyst loading in heterogeneous catalytic continuous-flow reactions are described by weight hourly space velocity (WHSV), which is an indicator of the reactant retention/residence time within the catalytic bed and defined as follows:

$$\text{WHSV}\ (hr^{-1}) = \frac{\text{Feed Concentration} \times \text{Feeding Flow Rate}}{\text{Mass of Catalyst}} \qquad (1.1)$$

The product samples collected from experiments were subjected to high performance liquid chromatography (HPLC) analysis to determine the amount of feedstock consumed and the amount of product formed and the results were calculated and presented in the terms of feedstock conversion and product selectivity and yield. Most experiments were performed in duplicates in order to insure the repeatability of the results and to minimize the experimental errors (<5%). Then, in figures and tables of the results the mean value of the data along with the corresponding errors have been presented, where applicable.

Comprehensive characterization of the catalysts was performed (where applicable) through various analyses including: thermogravimetric analysis (TGA) for thermal stability of the catalyst structure, X-ray diffraction (XRD) for crystalline structure of the catalyst, temperature programmed desorption of ammonia (TPD-NH_3) for total acidity and the strength of the acid sites on the catalyst surface, Brunauer-Emmett-Teller (BET) for surface area as well as pore size distribution (PSD) of the catalyst surface, Fourier transform infrared (FT-IR) spectrometry for functional groups of the catalyst and pyridine adsorbed FTIR (Py-FTIR) for presence and ratio of the Lewis and Brønsted acid sites on the catalyst surface.

1.4 Thesis Overview

Chapter 1 provides a general introduction and background to the importance of replacing fossil fuels (for energy and chemicals production) with biomass-derived fuels and materials, introduction of the HMF as an important key intermediate and building block that can be converted into potential fuels and various valuable chemicals as well as synthesis of HMF and its reaction pathways. The research objectives, approaches and methodology and thesis structure are also outlined.

Chapter 2 presents a detailed overview of the available literature on the production of HMF using fructose, glucose, disaccharides and polysaccharides in aqueous and organic single phase, biphasic and ionic liquid reaction media as well as a review on the isomerization of glucose to fructose as an important intermediate step in the production of HMF. In each section, the effects of different homogeneous and heterogeneous catalysts are studied. At the end of the chapter a summary of the literature review and the knowledge gaps are presented and discussed.

Chapter 3 presents the results of a catalyst screening study on glucose isomerization to fructose using different solid base catalysts in a continuous-flow tubular reactor. The studied catalysts were characterized comprehensively and their activities in the terms of glucose conversion and fructose selectivity and yield were compared in catalytic experiments. The effects of reaction temperature and calcination temperature of the catalyst were studied in the experiments. The stability of the selected catalysts was also tested over time to investigate the possibility of reusing the catalysts. Finally, some selected used catalysts were also analysed in order to study the catalyst deactivation mechanism.

Chapter 4 details the investigation of the glucose isomerization to fructose over activated hydrotalcite catalyst in a continuous-flow tubular reactor. The studied catalyst was characterized comprehensively and its activity in the terms of glucose conversion and fructose selectivity and yield was discussed. The effects of different reaction conditions including reaction temperature and retention time (in terms of feeding flow rate and catalyst loading) were studied. Finally, the feasibility of reactivating, recycling and reusing the used catalyst was examined.

Chapter 5 focuses on the HMF production from fructose dehydration in a biphasic media using a continuous-flow tubular reactor in the presence of different solid acid catalysts. Comprehensive characterization of the studied catalysts was performed and their activities in the terms of fructose conversion and HMF selectivity and yield were compared. The effects of different operating conditions including reaction temperature, feeding flow rate, initial fructose concentration, catalyst loading and presence of extracting organic solvent and phase transfer catalyst (PTC) were studied to find the best operating condition for the maximum HMF yield. The stability of the selected catalysts was also tested over time to investigate the possibility of reusing the catalysts. Finally, some selected used catalysts were also analysed in order to study the catalyst deactivation mechanism.

Chapter 6 describes the HMF production from glucose dehydration in a biphasic media using a continuous-flow tubular reactor in the presence of different solid acid catalysts and combinations of solid acid and base catalysts. Characterization of the studied catalysts was performed and their activities in the terms of glucose conversion and HMF selectivity and yield were compared in catalytic experiments. The effects of different experimental conditions including reaction temperature, feeding flow rate and organic to aqueous phase ratio were studied to find the best operating condition for the maximum HMF yield. The kinetics of the glucose conversion reaction in the presence of niobium phosphate catalyst was also studied and the kinetics parameters were determined. The stability of the selected catalysts was also tested over time to investigate the possibility of reusing the catalysts. Finally, some selected used catalysts were also analysed in order to study the catalyst deactivation mechanism.

Chapter 7 explores the HMF production from industrial grade sugar syrups derived from corn and wood in a biphasic media using a continuous-flow tubular reactor in the presence of niobium phosphate as the solid acid catalyst. The stability of the catalyst was also tested to investigate the possibility of reusing the catalyst and the feasibility of regeneration, recycling and reusing the used catalyst was also examined. Finally, the insoluble humins produced during the reaction as the main by-product was characterized in order to achieve better understanding about the reaction mechanism and the nature of insoluble humins as the main factor responsible for the catalyst deactivation.

Chapter 8 presents the main conclusions obtained from the present research and makes some recommendations for future works in this area.

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Chapter 2

2 Literature Review

So far, many attempts have been done by researchers for production of HMF from fructose, glucose and other biomass sources using a variety of solvents, catalysts, and reaction conditions. Until the 1980s, most researchers focused on homogeneous catalysts and water, a regular solvent for sugars and their derivatives.[1] Recently, there has been a shift from aqueous media to alternative solvents for HMF synthesis with higher selectivity and overall yield. HMF yield has been reported to be improved by the use of organic solvents such as dimethylsulphoxide (DMSO)[2], dimethylformamide (DMF)[3], dimethylacetamide (DMA)[4], acetonitrile (ACN)[5], methyl isobutylketone (MIBK)[6], dichloromethane (DCM)[7], tetrahydrofuran (THF)[8] and ethyl acetate (EA)[9] as the efficient reaction media and/or extracting solvents as well as ionic liquids (IL) for HMF synthesis and isolation. However, the use of organic solvents for HMF synthesis renders an inherent challenge in product isolation and solvent recovery. More efficient synthesis and separation methods are still required to be developed for cost-effective production of HMF at a large scale.

Based on the solvent system used for synthesis of HMF from carbohydrates, the processes can be divided into three main groups: single-phase systems (aqueous or organic solvent), biphasic systems (aqueous and organic solvents), and ionic liquid systems. These three types of systems will be reviewed here.

2.1 HMF Synthesis in Single-Phase Systems

As mentioned above, in the earlier researches on formation of HMF, single phase systems especially aqueous systems were used. The selection of water as the solvent in the reactions was mainly due to the high solubility of sugars in water. Moreover, water was considered as the cheapest and greenest solvent with abundant supply and can be used as an environmentally friendly medium.[10] Application of hot-compressed water or subcritical water has also been reported in literature.[11] Water at elevated temperature and pressure (less than critical points) has remarkable properties. The dielectric constant of water affecting its polarity decreases significantly compared to ambient water. This increases the solubility of hydrophobic organic materials such as free fatty acids, which are normally more soluble in non-polar solvents.[12,13] Furthermore, the ionic product of water at hot-compressed conditions increases, which releases more H^+ and OH^- in water promoting the acid or base-catalyzed reactions.[12] These characteristics of subcritical water play important roles in dehydration reactions. However, the yields of HMF in water were relatively low and also it is difficult to extract HMF from the water phase due to its high water solubility. As a result, organic solvents became of the main interest. The HMF synthesis in single phase systems (aqueous and organic) is discussed in this section based on different feedstock used (i.e., fructose, glucose, disaccharides and polysaccharides).

2.1.1 HMF Synthesis in Aqueous Single-Phase Systems

2.1.1.1 Fructose Dehydration

Fructose Dehydration without Catalyst

Dehydration of fructose to HMF in aqueous single phase system without catalyst was studied by a number of researchers. Hansen et al. investigated fructose dehydration at 160 ºC (heated by microwave irradiation) and 5 min reaction time. Only 1% HMF with 28% selectivity was produced from 30 wt% initial fructose concentration. Increasing temperature to 190 ºC, while keeping the other operating conditions constant, improved the yield to 36% with 54% selectivity.[14] With the same heating system (microwave irradiation), Qi et al. studied the production of HMF from fructose in water for 5 min. Without using catalyst and at 200 ºC 13.2% HMF was produced with 28.2% fructose conversion and 46% HMF selectivity.[15] It seems that HMF formation from fructose is more favourable at higher temperatures when no catalyst is used. This was also confirmed by the work of Watanabe et al. in which fructose dehydration in water without catalyst was studied at 200 ºC and 5 min. The experiment resulted in 21% HMF yield with 40% and 53% fructose conversion and HMF selectivity, respectively.[16]

Asghari and Yoshida showed that in the absence of catalyst, hot compressed water has the potential to decompose the fructose to HMF. However, a relatively low HMF yield from dehydration of fructose was observed, due to side reactions.[11] The authors mentioned the rehydration of HMF into the levulinic acid and formic acid as one of the main side reactions under normal conditions. They stated that in subcritical water the rehydration of HMF is relatively low due to the similarity of dielectric constant of subcritical water to that of organic solvents. However, another main side reaction which is polymerization of fructose and/or HMF occurs in both normal and subcritical conditions. The authors also investigated the influence of reaction conditions such as reaction temperature and time on the uncatalyzed dehydration of fructose to HMF. It was found that temperature has a strong influence on the reaction and increasing temperature from 200 to 260 ºC could increase the decomposition of fructose as well as formation of other by-products. HMF yield was as high as 23% at 260 ºC and decreased at higher temperatures due to decomposition and polymerization reactions of both HMF and fructose. At 240 ºC, increasing the reaction time from 0 to 200 sec increased the decomposition of fructose and HMF yield. However further increase in reaction time led to decreased HMF yield due to the side reactions.

Fructose Dehydration with Homogeneous Catalyst

For gaining a high HMF yield and selectivity, the choice of catalyst is very important. Several kinds of homogeneous and heterogeneous catalysts have been employed in this process. Homogeneous catalysts were applied in earlier works on dehydration of fructose. Kuster et al. investigated the conversion of fructose to HMF at 95 ºC catalyzed by HCl. The conversion rate of the fructose was proportional to the acidity of the solution. The high concentration of HCl (0.25-2 M) resulted in formation of levulinic acid from HMF. The highest HMF yield was 30% with 400 mol% HCl and 9 wt% initial fructose concentration and the highest selectivity was around 60%.[17]

Dehydration of fructose in water in the presence of H_2SO_4 and NaOH as homogeneous catalysts at 200 ºC with microwave irradiation heating was reported by Qi et al. The highest HMF yield with H_2SO_4 as a catalyst (50 wt%) was 47% and the selectivity was 48% with 5 min residence time and 2 wt% initial fructose concentration.[15]

Daorattanachai et al. investigated the effects of acid and base catalysts (H_3PO_4 and NaOH) on conversion of fructose to HMF in hot compressed water.[18] They reported that fructose could be easily dehydrated to HMF and therefore the addition of sodium hydroxide or phosphoric acid provided a small effect on fructose conversion. With or without catalysts, the fructose conversion was nearly comparable at 82-92%. The HMF yield was highest at 29% over phosphoric acid catalyst. The authors also investigated the effects of reaction temperature and time in the presence of phosphoric acid. Fructose conversion showed high values (>85%) for all temperatures in the range of 200 to 270 ºC and did not change much with temperature. At temperatures higher than 200 ºC, HMF yields decreased sharply from 29% to 0% which was attributed to the formation of insoluble humins at higher temperatures. Fructose conversion showed high values (>90%) at reaction times between 0 to 30 min. The HMF yield increased with the prolongation of time from 0 to 5 min and then decreased greatly afterwards. The authors suggested that the increase in the reaction time improves not only the formation of products, but also their decomposition rate.

Asghari and Yoshida studied the acid-catalyzed dehydration of fructose by using a variety of organic and inorganic acids (hydrochloric, sulfuric, phosphoric, oxalic, citric, maleic and p-toluenesulfonic acids) in hot compressed water at 240 ºC and 120 sec of reaction time.[11] Their results showed that a higher HMF yield could be obtained at pH values in the range of 2-2.5. At pH=2, phosphoric acid gave the highest HMF yield (65%) compared to other acids. At higher pH values, fructose and/or HMF were oligomerized or polymerized to yield more soluble polymeric by-products and thus lower yields of HMF were observed. The type of acid also found to have some influence on the stability of the intermediates. HCl showed a greater catalytic effect on the rehydration of HMF to levulinic and formic acids and thus lower HMF yields were obtained by using this catalyst. The authors also investigated the effects of temperature, reaction time and initial fructose concentration in the presence of phosphoric acid. The HMF showed the maximum yield of 65% in the temperature range of 230 to 250 ºC and 120 s of reaction time. It also had a decreasing trend as the initial concentration of fructose increased. This was attributed to the increasing possibility of polymerization and a destabilizing effect of fructose on HMF.

Fructose Dehydration with Heterogeneous Catalyst

At present, a significant number of acid-catalyzed reactions are still carrying out with conventional homogeneous acids. However, several problems such as toxicity, corrosion, difficulty of separation and recovering of the products and catalyst have been reported.[19]

Heterogeneous or solid catalysts are more advantageous compared to homogenous ones due to their lower impact on the systems and global environment and reusability.[16,20] They are easier to be separated and recycled and they will facilitate large-scale industrial operations and production.

Zeolites, heteropoly compounds, oxides, phosphates and resins have been widely used as heterogeneous catalysts for dehydration reactions [19], however most solid acid catalysts such as sulfated zirconia were found to be unsatisfactory in water with low HMF yields of 36% even at high temperatures.[21] The use of aluminosilicate as a heterogeneous catalyst for production of HMF from fructose was patented in 1992 and HMF yields of 20-32% were claimed with zeolites and protonic montmorillonite at 145 °C.[22] Fan et al. reported the HMF selectivity and fructose conversion of around 27% and 55%, respectively in the presence of a heteropolyacid salt, $Ag_3PW_{12}O_{40}$ as a heterogeneous catalyst for fructose dehydration.[23]

Many catalytic sites and high thermal stability of solid acids are required for HMF production and a good solid catalyst should keep its sufficient catalytic activity in the reaction media.[24] Niobium containing catalysts have attracted much interest due to their strong acid properties which can be preserved in polar liquids. Hydrated niobium pentoxide, also called niobic acid ($Nb_2O_5.nH_2O$) is commonly used due to cheapness, low toxicity and easy handling.[21] The Brønsted acidity of niobic acid is very high ($H_o \leq -5.6$). Niobium phosphate, another niobium containing catalyst, has also acid properties ($H_o \leq -8.2$) with a higher ratio of Lewis/Brønsted acid sites.[19] Niobic acid is readily prepared by the hydrolysis of $NbCl_5$ or $Nb(OC_2H_5)_5$ and is an amorphous metal oxide composed mainly of distorted NbO_6 octahedra and NbO_4 tetrahedra. Nb-O bonds are highly polarized, so that a part of the surface OH groups function as Brønsted acid sites, while NbO_4 tetrahedra function as Lewis acid sites.[25] Niobic acid, niobium or vanadium phosphates have been applied as heterogeneous catalysts for dehydration of fructose and inulin and reported to result in high yields up to 50% at 80-100 °C which is the highest HMF yield reported in pure water without assistance of an extractive solvent.[22]

The catalytic properties of niobium phosphate was studied in dehydration of fructose to HMF by Carlini et al.[26] The niobium phosphate catalyst showed high activity and resulted in high HMF selectivity (85-100%) at 100 °C, however these selectivities were obtained at low fructose conversion of 25-35%. The highest reported selectivity at 50% conversion was around 60%.

Fructose Dehydration in Continuous Process

Most of the researches in this field were performed in batch mode and little attention has been paid to using continuous flow reactor which is more desirable for application in large scale for industrial and commercial production. Some researchers have reported reactions of fructose in water using flow reactors. Aida et al. investigated the dehydration of fructose in water in a flow reactor at 350 and 400 °C and up to 100 MPa of pressure in the absence of catalyst. It was reported that high temperature and high pressure conditions increased retro-aldol reactions and water related reactions such as dehydration and hydration reactions. Under these operating conditions, the main products were retro-aldol products with a mixture of dihydroxyacetone and glyceraldehyde. The maximum HMF yield (7.7%) was obtained at 350 °C and a residence time of 0.78 sec.[27]

Further research on flow reactor at 240-260 °C was conducted by Tarabanko et al. They used phosphoric acid as a homogeneous catalyst and the optimum HMF yield they obtained was 40%. They reported that a decrease in acid concentration resulted in higher optimum temperatures which also yielded a higher concentration of HMF.[28]

In general, focusing on the best yield and selectivity, there is no clear trend in the yields reported from homogeneous and heterogeneous catalysts. However, it is obvious that in the absence of catalyst lower yields of HMF are obtained. It was also reported that with a higher conversion rate, lower selectivity was observed. This is likely due to the fact that when conversion increases, rehydration and polymerization reactions of HMF to levulinic acid and formic acid as well as humins also increase. In order to achieve a higher selectivity, the rehydration reactions of HMF should be suppressed by either stabilization or removing HMF from the reaction environment.[1]

2.1.1.2 Glucose Dehydration

Although previous works declare that fructose (ketose) is much more reactive and selective toward HMF than glucose (aldose), the use of glucose as the feedstock for bulk production of HMF is considered more cost-effective because glucose is much cheaper and more readily available in the nature than fructose.[29] It has been reported that HMF selectivity and yield from glucose is less, to a great extent, than that from fructose under the same reaction conditions (i.e., fructose is much more readily converted to HMF than glucose).[30] This can be attributed to the isomerization step of glucose to fructose as well as the abundance of acyclic fructose compared to acyclic glucose and more stable ring structure of glucose.[31] Isomerization of glucose to fructose as an intermediate step for production of HMF is of great importance.[32,33] Thus in this section, the isomerization reactions will be also reviewed.

Isomerization of Glucose to Fructose

Catalytic conversion of glucose into fructose through isomerization as an intermediate step for production of valuable furan derivatives and platform chemicals has attracted a lot of attention.[32,33] Currently, the isomerization of glucose into fructose is carried out in large industrial scale by immobilized enzymes for bulk production of high fructose corn syrup (HFCS). However, this process has major drawbacks such as the need of high amounts of expensive enzyme, limited operating temperature range due to the sensitivity of enzymes to process parameters and the possibility of microbial growth in the system.[32,34,35] Chemical catalysts have been used as an alternative to enzymes in the isomerization process and are reported to make the process more rapid and robust than the biochemical process. Moreover, the chemical catalysts have wider operating temperature range, longer lifetime and higher resistance to impurities.[36] However, the catalytic isomerization process is accompanied by production of a variety of by-products. Thus a highly selective, efficient and inexpensive catalyst is essential to control the undesirable reactions and improve the reaction kinetics.

Glucose isomerization to fructose is catalyzed both by Lewis acids and Brønsted bases. However, it has been widely reported that fructose yields are typically low for Brønsted bases (<10%) and high fructose selectivity can only be obtained at low glucose conversion. Therefore, recent works focused on the more promising Lewis acid-catalyzed route.[37] Liu et al. studied the amine-catalyzed isomerization of glucose to fructose. It was shown that amines could catalyze the isomerization of glucose to fructose with the same performance of the Lewis acid catalysts. Most of the fructose was formed within minutes: the yield was of 29% after 15 min and reached 31% after 30 min of reaction at 100 °C and a catalyst loading at 10 mol% relative to glucose. The highest yield of 32% with a fructose selectivity of 63% were reached after 20 min at 100 °C.[37]

Yu et al. reported isomerization of glucose into fructose by using as-synthesized Mg–Al hydrotalcite (HT-A), calcined Mg–Al hydrotalcite (HT-C), and rehydrated Mg–Al hydrotalcite (HT-R) catalysts. HT-R catalyst exhibited the highest fructose yield of 35% at 80 ºC compared to other catalysts tested. The enhanced catalytic performance of HT-R was attributed to the abundant weak base sites of this catalyst exposed by the rehydration process. The authors also investigated the effects of temperature and reaction time on the isomerization process. Glucose conversion was found to increase when temperature was raised from 70 to 110 °C, while the fructose selectivity decreased with increasing temperature due to the enhanced amount of degradation products at higher temperatures. Fructose production was improved by longer reaction times up to 3 hr, however, no significant increase was observed after this time.[36]

Watanabe et al. studied the catalytic activity of ZrO_2 and TiO_2 (rutile and anatase) at 200 ºC of reaction temperature and 5 min reaction time and reported enhanced glucose conversion in the presence of anatase TiO_2.[16,38] They also compared the performance of these metal oxides with homogeneous acid and alkali catalysts (NaOH and H_2SO_4 solutions) and reported the highest conversion of about 80% with anatase TiO_2. No considerable effect with NaOH and rutile TiO_2 was observed and fructose formation was inhibited by H_2SO_4.[38]

Glucose Dehydration without Catalyst

Work by Jing and Lu on glucose decomposition in water at 220 ºC under pressure of 10 MPa without catalyst showed HMF yield of more than 30% and 45% selectivity at 71%

conversion when 1% glucose concentration was used. The duration of the reaction was 30 min.[39]

Watanabe et al. reported glucose dehydration in hot compressed water (initially pressurized by Ar at 2.5 MPa) at 200 ºC without catalyst with 9 wt% glucose concentration. Glucose gradually converted (30% conversion at 10 min of reaction time) to form liquid products. Initially some fructose formed and then disappeared with the formation of HMF. The HMF yield was 7% with 23% selectivity.[38]

Glucose Dehydration with Homogenous Catalyst

The dehydration of glucose in the presence of a catalytic amount of lanthanide (III) salt in water was performed by Seri et al. The lanthanide (III) ions were found to be excellent Lewis acid catalysts giving HMF without accompanying the undesirable further decomposition to levulinic acid, a process which is often observed upon dehydration with conventional Brønsted acids. It was reported that the amount of lanthanide (III) catalysts dramatically enhanced the rate of HMF production. 363 μmol of HMF was produced from glucose dehydration at 140 ºC for 1 hr.[40]

Watanabe et al. reported glucose dehydration in hot compressed water (initially pressurized by Ar at 2.5 MPa) at 200 ºC with 9 wt% glucose concentration. The authors used H_2SO_4 and NaOH as homogeneous catalysts. Under acidic conditions, HMF formation from glucose was slightly enhanced. On the other hand, in the presence of NaOH, glucose conversion was almost the same as that without using catalyst, and HMF formation was suppressed.[38]

Another work by homogeneous catalysts was performed by De et al. who studied glucose dehydration in water by a homogeneous $AlCl_3$ catalyst. With 5 wt% glucose concentration and 50 mol% catalyst loading at 120 ºC (heating by microwave irradiation), they obtained 40% HMF yield at a residence time of 20 min.[41]

Glucose Dehydration with Heterogeneous Catalyst

In the field of glucose dehydration in the presence of heterogeneous catalyst, Chareonlimkun et al. reported conversion of glucose in hot compressed water at 200-400

°C using TiO_2, ZrO_2 and sulfated zirconia (SO_4-ZrO_2) as catalysts. They claimed that TiO_2 and SO_4-ZrO_2 enhanced the dehydration reaction resulting in high HMF yields with fewer by-products. Whereas ZrO_2 promoted the isomerization reaction and consequently considerable amount of fructose was observed in the liquid product. Reactions at 250 °C with 100 wt% TiO_2 catalyst loading yielded 27% HMF with 77% glucose conversion and 2-2.5% fructose product in a 5 min reaction time.[42]

In another work by Chareonlimkun et al. reaction at 250 °C in the presence of TiO_2-ZrO_2 produced 29% HMF with 67% selectivity in the same operating conditions as the previous work. This time the glucose conversion was 44%.[43]

Nakajima et al. studied glucose decomposition in 1000 wt% niobic acid ($Nb_2O_5.nH_2O$) as the heterogeneous catalyst. It yielded 52% HMF with 57% selectivity at 92% conversion. The corresponding reaction time and temperature were 3 hr and 120 °C, respectively.[25]

Glucose Dehydration in Continuous Process

The continuous production of HMF from glucose in aqueous single-phase media was studied by Aida et al. at high temperatures (up to 400 °C) and high pressures (up to 80 MPa). It was found that increasing pressure and thus increasing the water density enhances the dehydration reaction to HMF but also accelerates the hydrolysis of HMF leading to the production of by-products. Increasing the temperature had the same effect on HMF yield. The higher pressure effect was attributed to the transition states. Water molecules participate in the transition state by forming the so-called "water bridge" and lower the transition energy, thus enhance dehydration reactions. Another explanation for the pressure effect was the increase in K_w of water at elevated temperature and pressures. The increase in K_w can promote the acid catalyst effect on the dehydration and hydration reactions. Due to the improved hydrolysis rate at high temperature and pressure, low yields of HMF (<10%) were reported in this study.[44]

2.1.1.3 Disaccharides and Polysaccharides Dehydration

Sucrose is a non-reducing disaccharide composed of glucose and fructose linked via their anomeric carbons. It is obtained commercially from sugarcane, sugar beet, and other plants and used extensively as a food and a sweetener. Just like fructose, sucrose have also been considered as a superior carbohydrate compound for production of furan-based chemicals.[45]

Carlini et al. studied the dehydration of sucrose to HMF in aqueous medium by using heterogeneous niobium phosphate catalyst at 100 ºC for 4 hr. They did not report any conversion of glucose moiety. However, when considering the both glucose and fructose moieties as substrate, a HMF yield of 14% was reported at 30% conversion from 13 wt% sucrose.[26]

Tarabanko et al. also studied the dehydration of sucrose to HMF but at a higher temperature range (250-260 ºC). They used a continuous flow process with 0.2 M sucrose in water and 0.6 M acetic acid as a homogeneous catalyst. The reported HMF yield was 40%. However, they did not mention whether this yield is based on glucose or fructose moiety or both of them.[28]

Production of HMF from inulin has also been reported in some literature. Inulins are a group of naturally occurring polysaccharides produced by many types of plants, industrially most often extracted from chicory. Wu et al. studied inulin dehydration in aqueous medium without catalyst at different temperatures and reaction times with a constant inulin loading of 5 wt% in all of the experiments. The highest HMF yield (53%) was obtained at 180 ºC and a CO_2 pressure of 6 MPa with a 1.5 hr residence time.[46]

Despite the most research efforts towards HMF production from edible carbohydrates such as glucose and fructose, using inedible resources such as lignocellulosic biomass as starting material would be preferable. Therefore, the development of efficient routes for converting inedible biomass into HMF is essential for achieving sustainable production of 5-HMF.

Mok et al. conducted cellulose hydrolysis experiments in the presence of homogeneous H_2SO_4 solution (20 mM) in water. The reported HMF yield was 5% at 215 ºC and 1 hr reaction time in a semi-batch flow process.[47]

In addition, Yin et al. published a work on hydrothermal conversion of cellulose to HMF in water. They tested the HMF formation yields without catalyst (pH=7) and also by adding acidic (pH=3) and alkaline (pH=11) solutions of HCl and NaOH as homogeneous catalysts, respectively. The temperature and reaction residence time ranged from 275-320 °C and 0-30 min, respectively. The HMF yields were in the order of acidic, neutral and alkaline solutions. The best result was under acidic condition at 300 °C and 0 min reaction time (excluding preheating time) which resulted in 21% HMF yield with 3 wt% of cellulose concentration. Due to the low HMF yield and also low purity of it, alkaline hydrothermal conversion of cellulose was not recommended for HMF production.[48]

Chareonlimkun et al. also investigated conversion of cellulose to HMF in an aqueous single-phase system. Experiments were conducted using heterogeneous catalysts TiO_2, ZrO_2 and sulfated zirconia (SO_4-ZrO_2) in hot compressed water at 200-400 °C. The best catalysts for cellulose dehydration were TiO_2 and ZrO_2 which resulted in 13% and 8.3% HMF yields with 37% and 33% selectivities, respectively. These results were obtained at 250 °C and 5 min residence time with 100 wt% catalyst loading and 9 wt% cellulose concentration for both reactions.[49]

Zhao et al. reported higher yields of HMF from cellulose hydrolysis and glucose dehydration in one pot under mild conditions in water by using heteropolyacid catalysts (HPA) $Cr[(DS)H_2PW_{12}O_{40}]_3$, $Cr[H_2PW_{12}O_{40}]_3$ and $H_3PW_{12}O_{40}$. The reactions were conducted at 150 °C for 2 hr by using 0.2 g of cellulose and 0.06 mM catalyst concentration. Results showed that $Cr[(DS)H_2PW_{12}O_{40}]_3$ has superior activity compared to other catalysts and resulted in 53% HMF yield with 68% selectivity.[50]

A summary of the previous works on carbohydrates dehydration to HMF in aqueous single-phase systems is listed in Table 2.1.

Table 2.1: Summary of the literature review on HMF synthesis in aqueous single-phase systems

Feed	Catalyst	Solvent	Temperature (°C)	Reaction Time	Conversion (%)	Yield (%)	Ref.
Homogenous Catalyst							
Fructose	HCl	Water	150	2 hr	74	43	[22]
Glucose	H_2SO_4	Water	200	300 sec	32	2.8	[38]
Glucose	NaOH	Water	200	300 sec	27	2	[38]
Fructose	H_2SO_4	Water	200	5 min [a]	97.3	47	[15]
Fructose	NaOH	Water	200	5 min [a]	72.9	2.7	[15]
Glucose	H_2SO_4	Water	200	3 min [a]	10.6	2.4	[15]
Glucose	NaOH	Water	200	3 min [a]	46.6	4.9	[15]
Fructose	HCl	Water	200	1 sec [a]	52	33	[51]
Glucose	$AlCl_3$	Water	120	20 min [a]	-	40.3	[41]
Fructose	$AlCl_3$	Water	120	5 min [a]	-	50.2	[41]
Glucose	-	Water	220	30 min	70	32.0	[39]
Cellulose	HCl	Water	300	0 min	-	20.7	[48]
Cellulose	NaOH	Water	300	0 min	-	9.8	[48]
Glucose	H_3PO_4	Water	230	5 min	80	10	[18]
Glucose	NaOH	Water	200	5 min	40	4.1	[18]
Fructose	H_3PO_4	Water	230	5 min	92	29	[18]
Frutose	NaOH	Water	200	5 min	81	20	[18]
Cellulose	H_3PO_4	Water	230	5 min	-	7.6	[18]
Cellulose	NaOH	Water	200	5 min	-	0.5	[18]
Fructose	H_3PO_4	Water	240	120 sec	-	65.3	[11]
Fructose	HCl	Water	240	120 sec	-	44.7	[11]
Fructose	H_2SO_4	Water	240	120 sec	-	40.6	[11]
Heterogeneous Catalyst							
Frcutose	NbPO-pH2	Water	130	30 min	57.6	45.0	[52,53]

Glucose	NbPO-pH7	Water	140	60 min	40.6	38.2	52,53
Fructose	Amberlyst-15	Water	130	30 min	61.6	31.3	53
Fructose	NbO	Water	100	70 hr	71	20	54
Fructose	NbOH	Water	180	2 hr	92	18	22
Glucose	NbOH	Water	200	2 hr	60	16	22
Glucose	H_3PO_4/ $Nb_2O_5.nH_2O$	Water	120	3 hr	92	52.1	25
Glucose	a-TiO_2	Water	200	300 sec	98	23	38
Fructose	TiO_2	Water	200	10 min	90.4	41.2	15
Fructose	ZrO_2	Water	200	5 min	65.3	30.6	15
Glucose	TiO_2	Water	200	5 min	63.8	18.6	15
Glucose	ZrO_2	Water	200	5 min	56.7	10.0	15
Glucose	TiO_2	Water	250	5 min	77	27	42
Glucose	ZrO_2	Water	250	5 min	75	17	42
Glucose	SO_4-ZrO_2	Water	250	5 min	79	22	42
Corncob	TiO_2-ZrO_2	Water	250	5 min	44	29	43
Cellulose	$Cr[(DS)H_2PW_{12}O_40]_3$	Water	150	2 hr	77.1	52.7	50
Fructose	Zirconium Phosphate	Water	240	120 sec	79.6	49.1	55
Glucose	Zirconium Phosphate	Water	240	120 sec	38.7	12.3	55
Fructose	Silver Exchanged Silicotungstic Acid (AgSTA)	Water	120	120 min	98.0	85.7	56
Sucrose	Silver Exchanged Silicotungstic Acid (AgSTA)	Water	120	160 min	92.4	62.5	56
Continuous Process							
Glucose	-	Water	350	1.6 sec	84.3	7.0	44
Fructose	-	Water	350	0.78 sec	64	7.7	27
Fructose	Phosphoric Acid	Water	240	3 min	-	40	57
Sucrose	Acetic Acid	Water	255	3 min	-	40	57

[a] Microwave Heating

2.1.2 HMF Synthesis in Organic Single-Phase Systems

2.1.2.1 Fructose Dehydration

The HMF produced by the dehydration of fructose in aqueous medium, could further rehydrates to produce levulinic and formic acids. The most popular approach to prevent this sequential reaction and improve HMF yield is using organic solvents as the reaction media. Application of different organic solvents such as acetone [58,59], methanol, acetic acid, DMSO [59–61], DMF [62] and DMA has been reported in literature for resolving the lack of selectivity in aqueous media.

Fructose Dehydration with Homogeneous Catalyst

Dehydration of fructose using dimethylsulphoxide (DMSO) as organic solvent at 100 ºC was studied by Brown et al. The experiments were performed with and without catalysts (acid and base). It was reported that the base catalysts suppressed the HMF formation while the acid catalysts enhanced it. The fastest conversion of fructose (0.75 hr) occurred with NH_4Cl as a catalyst. At 50 ºC the order of catalytic effects was NH_4CI > NH_4Br > Et_3NHCl > Et_3NHBr. Since separation of produced HMF from DMSO was difficult, they also tried using other organic solvents such as sulpholane, DMF, ethyl acetate and butyl acetate in the presence of NH_4Cl. Among these solvents, sulpholane and DMF had the same problem as DMSO. In ethyl acetate the reaction rate was less than other solvents. The complete conversion was obtained after 30 hr at 77 ºC and with 58% HMF yield from 5 wt% fructose. The butyl acetate resulted in incomplete conversion after 16 hr at 100 ºC with 31% HMF yield from fructose of the same concentration.[62]

Wang et al. studied the dehydration of fructose in DMSO, DMA, 1,4-dioxane and the mixture of PEG-400 and water as organic solvent in the presence of rare earth metal triflates. The reactions were carried out at 120 ºC for 2 hr. The obtained HMF yields were 83.3%, 49.8%, 16.3% and 12.9% in DMSO, DMA, 1,4-dioxane and the mixture of PEG-400 and water, respectively. The fructose conversion was reported to be 100% in DMSO, 98.4% in DMA, 86.2% in 1,4-dioxane and 37% in PEG-400/water. The authors claimed that DMSO is an efficient solvent for promoting the dehydration of fructose to HMF, as it efficiently inhibits the formation of by-products such as levulinic acid and formic acid. The

HMF yield was also found to be closely dependent on the reaction temperature, reaction time, dosage of catalyst and concentration of fructose. To obtain higher yields of HMF, higher temperatures up to 120 ºC, shorter reaction times (2 hr), lower fructose concentrations (2%) and appropriate amount of catalyst (0.004 g) were essential. Further increase in temperature from 120 to 130 ºC resulted in reduction of HMF yield due to the polymerization of HMF or cross-polymerization between fructose and HMF and production of polymers and humin matters at higher temperatures. Reaction times longer than 2 hr, were also found to cause a drop in the HMF yield owing to the formation of undesired by-products. Catalyst dosage affected the HMF yield leading to an increase in the yield by increasing the amount of catalyst but did not change fructose conversion. HMF yield was found to decrease gradually with increasing initial fructose concentration when fructose concentration exceeded 2 wt%. This was considered to be as a result of self-polymerization of HMF or cross-polymerization between fructose and HMF at higher initial concentration of fructose, giving rise to the formation of brown black soluble polymers and insoluble humins.[63]

Fructose Dehydration with Heterogeneous Catalyst

Shimizu et al. used DMSO with a variety of catalysts such as ion exchange resins, zeolites, heteropolyacids and base heterogeneous catalysts (6 wt%) at 120 ºC and a 2 hr reaction time. They presented two simple ways for increasing HMF yield and selectivity in the solid acid catalyzed reaction. The first method was water removal from the reaction by using mild evacuation at 0.97×10^5 Pa. This method will prevent further rehydration of HMF to levulinic and formic acid and also the reaction of partially dehydrated intermediates to condensation products. The second method was to reduce the particle size of the Amberlyst-15 resin. This method was expected to increase the removal of adsorbed water from the surface and near-surface of the catalyst. They claimed that by using a resin catalyst with particle size of 0.15-0.053 mm, 100% HMF yield was obtained at high fructose concentration (50 wt% in DMSO). Base catalysts were found to suppress the HMF formation.[64]

Yan et al. studied conversion of fructose to HMF in DMSO at 130 ºC in the presence of SO_4^{2-}/ZrO_2 and $SO_4^{2-}/ZrO_2\text{-}Al_2O_3$ catalysts for 4 hr. It was found that the HMF yield was about 72% without catalyst and decreased monotonically with the basicity of the catalysts. This evidenced that DMSO was an excellent solvent for the fructose dehydration to HMF. The HMF yield was mentioned to be as a result of an integrated effects of suitable amounts of acid and base sites on the surface of the catalysts.[29]

Some authors studied using co-solvents for single phase fructose dehydration. Qi et al. reported HMF production in acetone-DMSO co-solvents with the ratio of 70:30 w/w at 180 ºC. They used sulfated zirconia as a solid acid catalyst. A high fructose conversion of 93.6% with HMF yield of 72.8% was obtained with a 20 min reaction time. It was reported that this catalyst was effective for fructose dehydration in organic co-solvents such as acetone-DMSO; however it has low catalyst activity in water.[65]

Fructose Dehydration in Continuous Process

Bicker et al. studied the effects of co-solvent on fructose dehydration in a continuous flow process. They mixed acetone and water (90:10) and investigated the effects of different reaction parameters such as temperature, pressure, catalyst concentration, solvent composition and residence time with H_2SO_4 as a homogeneous catalyst. With a 10 mM catalyst loading, at temperature of 180 ºC, pressure of 20 MPa and a 2 min reaction time, they obtained a 75% HMF yield at 98% conversion with 77% selectivity.[58]

Schön et al. reported the application of a continuous flow reactor in fructose dehydration to HMF in the presence of HCl as a homogeneous catalyst and DMSO as solvent. They used a continuous cartridge-based reactor system and a semi-continuous stop-flow microwave reactor and compared the results from the two reactors. Higher HMF yields were observed for the continuous flow process at 180 ºC compared to the semi-continuous reactor at 150 ºC (90.3% vs. 85.6%). However, formation of levulinic acid was reported in the continuous flow process under all investigated conditions, while levulinic acid levels in the microwave reactor sample were below the HPLC detection limit under optimized conditions.[66]

In summary, literature shows that the HMF yields and selectivity from fructose were much higher in organic solvents than those in aqueous solutions. Yields higher than 90% were reported by using solvents such as DMSO, DMF and DMA.[1,64,67]

2.1.2.2 Glucose Dehydration

A number of research groups have examined the feasibility of using organic solvents as reaction media for glucose dehydration to HMF. Comparing the results of glucose dehydration in organic solvents with those in aqueous systems shows that the yields are generally higher in organic solvents.

Glucose Dehydration with Homogeneous Catalyst

Yan et al. studied HMF formation from glucose by using DMSO as the solvent. In the absence of catalyst and with 7.6 wt% glucose concentration, 4.3% HMF was produced at 130 ºC and 94% conversion after 4 hr.[29]

In a study by Binder and Raines glucose dehydration in DMA containing 10 wt% LiBr was investigated with the main focus on using different homogeneous metal chlorides catalysts. They performed their experiments by loading a 6 mol% solution of $CrBr_3$, $CrCl_2$ and $CrCl_3$ at 100 ºC. The glucose concentration was 10 wt%. The highest HMF yield of 80% and 79% was observed by using $CrBr_3$ and $CrCl_3$ in 6 hr reaction time, respectively. $CrCl_2$ produced 76% of HMF with a lower residence time (4 hr).[4]

Chen and Lin also studied catalytic dehydration of glucose to HMF in an organic solvent by using $CrCl_3$, $CrCl_2$ catalyst. They also tested $SnCl_4$ and $SnCl_2$ as homogeneous catalysts. The reactions were performed in caprolactam (CPL) containing lithium chloride (LiCl) as solvent with a 3:1 molar ratio at 100 ºC and a 3 hr reaction time. They claimed that the catalysts were uniquely effective, leading to the conversion of glucose to HMF with yields of 55-65%. The highest HMF yield (65%) with 66% selectivity was obtained with $SnCl_4$ at 98% conversion.[68]

In another publication, Seri et al. investigated the catalytic activity of lanthanide (III) ions in DMSO solvent for the dehydration of glucose yielding HMF. Since lanthanide (III) ions are excellent Lewis acid catalysts, they can enhance the HMF formation reaction without leading to undesirable rehydration reactions, which result in the formation of levulinic acid. They reported an HMF yield of 9.8% at 120 ºC and 2 hr reaction time with 5 mol% of catalyst loading.[69]

Glucose Dehydration with Heterogeneous Catalyst

In the field of using heterogeneous catalyst, Ohara et al. compared different organic solvents with different solid acid and/or base catalysts for selective dehydration of glucose. The solvents tested were DMA, DMF, DMSO and ACN, the acid catalyst was Amberlyst-15 (a strong acidic ion-exchange resin) and the base catalyst was hydrotalcite (a layered clay compound). No HMF formation was observed when either catalyst was used separately. However, HMF was obtained by using a combination of them with a ratio of 2:1 w/w. At 100 ºC and 3 hr reaction time with 3 wt% glucose concentration, different solvents resulted in different yields of HMF with the same catalyst loading (300 wt%). The reactions with ACN and DMA yielded 10% and 14% HMF with 12% and 14% selectivities, respectively. While using DMF and DMSO as solvent yielded 41% and 12% HMF with 57% and 13% selectivities, respectively. They also showed that addition of a small amount of water to the solvent improved HMF selectivity.[5]

Yan et al. investigated HMF formation reactions by using DMSO solvent at 130 ºC and SO_4^{-2}/ZrO_2 and SO_4^{-2}/ZrO_2-Al_2O_3 as the heterogeneous catalysts. An HMF yield of 47.6% with 49% selectivity was obtained from a 7.6 wt% glucose concentration within 4 hr over SO_4^{-2}/ZrO_2-Al_2O_3 with a Zr-Al mole ratio of 1:1. This was much higher than the reaction without catalyst in which 4.3% HMF was produced at 130 ºC and 94% conversion. They showed that the catalyst with higher acidity and moderate basicity was more favorable for HMF formation.[29]

2.1.2.3 Disaccharides and Polysaccharides Dehydration

Takagaki et al. investigated the dehydration of sucrose and cellobiose to HMF over solid acid and base catalysts, Amberlys-15 and Mg-Al hydrotalcite (HT) in DMF as organic solvent. Experiments were conducted through a one-pot reaction under mild conditions. 54% HMF at 58% conversion from sucrose and 35% HMF at 52% conversion from cellobiose were obtained using 0.1 g substrate in 3 ml DMF with 0.1 g of either catalyst at 120 ºC and a 3 hr reaction time.[3]

Dehydration of sucrose to HMF in organic solvents was also studied by Seri et al. The reactions were carried out at 100-120 ºC in six solvent systems including DMSO, DMF, DMA, sulpholane, 1,4-dioxane and 1-butanol in presence of $LaCl_3$. Among these solvents, DMSO gave the best yield for sucrose conversion (47%) at 120 ºC and 2 hr reaction time by adding 5 mol% of the catalyst.[2]

A summary of the previous works on carbohydrates dehydration to HMF in organic single-phase systems is listed in Table 2.2.

Table 2.2: Summary of the literature review on HMF synthesis in organic single-phase systems

Feed	Catalyst	Solvent	Temperature (ºC)	Reaction Time	Conversion (%)	Yield (%)	Ref.
Homogenous Catalyst							
Fructose	Sulfonated Carbon	THF/DMSO	160	60 min	99.0	98.0	[70]
Fructose	Tetraethyl Ammonium Chloride (TEAC)	TEAC	120	70 min	100	81.3	[71]
Fructose	Rare Earth Metal Triflates	DMSO	120	2 hr	100	83.3	[63]
Fructose	Rare Earth Metal Triflates	DMA	120	2 hr	98.4	49.8	[63]
Fructose	Rare Earth Metal Triflates	1,4-dioxane	120	2 hr	82.6	16.3	[63]
Fructose	Rare Earth Metal Triflates	PEG-400/Water	120	2 hr	37.0	12.9	[63]
Cellulose	H_2SO_4	THF	190	120 min	84	44	[59]
Glucose	$AlCl_3$	DMSO	140	5 min	-	52.4	[41]
Fructose	$AlCl_3$	DMSO	140	5 min	-	69.4	[41]
Glucose	$CrCl_3$	CPL-LiCl	100	3 hr	98	66.7	[72]
Glucose	$SnCl_4$	CPL-LiCl	100	3 hr	99	64.7	[72]
Heterogeneous Catalyst							
Xylose	Amberlyst-15/Hydrotalcite	DMA	100	3 hr	57	48	[73]
Glucose	Amberlyst-15/Hydrotalcite	DMA	100	3 hr	60	45.6	[3]
Glucose	Nafion NR50/Hydrotalcite	DMA	100	3 hr	60	16.2	[3]

Fructose	Amberlyst-15/Hydrotalcite	DMA	100	3 hr	>90	70	74
Glucose	Sn-Mont	THF/DMSO	160	3 hr	98.4	53.5	75
Glucose	Amberlyst-15/HT	DMF	80	9 hr	73	42	5
Glucose	Amberlyst-15/HT	DMSO	80	3 hr	41	25	5
Glucose	Amberlyst-15/HT	DMA	100	3 hr	97	14	5
Glucose	SO_4^{2-}/ZrO_2	DMSO	130	4 hr	95.2	19.2	29
Glucose	$SO_4^{2-}/ZrO_2\text{-}Al_2O_3$	DMSO	130	4 hr	97.2	47.6	29
Fructose	SO_4^{2-}/ZrO_2	DMSO	130	4 hr	100	68.2	29
Fructose	$SO_4^{2-}/ZrO_2\text{-}Al_2O_3$	DMSO	130	4 hr	99.6	64.2	29
Fructose	Sulfated Zirconia	Acetone/DMSO	180	20 min	93.6	72.8	65
Glucose	$CrCl_2$/TEAC	DMSO	130	1 hr	-	49.3	76
Continuous Process							
Fructose	H_2SO_4	Acetone/Water	180	2 min	98	75	58
Fructose	HCl	DMSO	150	2 min [a]	-	85.6	66
Glucose	HCl	DMSO	220	10 min [a]	-	29.4	66

[a] Microwave Heating

2.2 HMF Synthesis in Biphasic Systems

An effective and alternative method to prevent the further rehydration of produced HMF to levulinic and formic acids and thus increase the HMF yields is removal (extraction) of HMF from the reaction mixture by either using an extracting solvent or a selective adsorbent (e.g. activated carbon).[30] Removing HMF from the reaction medium using methyl isobutyl ketone (MIBK) as the extracting solvent was first introduced in by Cope in 1959 [31] and has since then been used by Kuster and van der Steen [77], Rigal et al. [78], and Moreau et al.[6] Extraction of HMF with other organic solvents such as primary and secondary alcohols, ketones and ethers have also been reported.[30] The second method involves the utilization of selective adsorbents such as activated carbon treatments. This method has also been largely used for the removal of the HMF produced in the thermal treatment of honey and fruit juices.[30] Besides activated carbon, the use of zeolites to separate HMF from fructose is also addressed in the literature.[30] In this section, previous studies on the use of organic solvents for HMF extraction in biphasic media are reviewed.

2.2.1 Fructose Dehydration

2.2.1.1 Fructose Dehydration with Homogeneous Catalyst

MIBK has been widely used as an extractive solvent for fructose dehydration. It has been considered as a good solvent for sugars dehydration in water that could suppress the undesired side reactions and extract more HMF into organic phase.[23] However, the partition coefficient of HMF for MIBK/water solution is close to unity which means that large amounts of MIBK are needed to extract HMF from the aqueous phase.[30] This problem could be solved by addition of modifiers to both organic and aqueous phases to improve HMF partitioning between the two phases and also to suppress side reactions.[30]

Hansen et al. studied aqueous dehydration of fructose to HMF with MIBK as extracting solvent and by addition of an inorganic salt as the modifier. Experiments were conducted at 150 °C and the reaction time was 45 min. Boric acid (H_3BO_3) was used as a homogeneous acid catalyst in the experiments. The effects of different catalyst loading showed that by increasing the amount of catalyst, HMF yield and selectivity increased as well. They also found that addition of the inorganic salt to the reaction solvent, improved both HMF yield and selectivity compared to those with no salt added. Although the HMF selectivity remained almost the same (65%) by using different inorganic salts, the best result of 52% HMF yield was obtained using 0.44 M $MgCl_2$.[79]

In another work, Román-Leshkov and Dumesic studied fructose dehydration in a biphasic system and found that an inorganic salt such as NaCl can significantly alter the extraction equilibrium of HMF. It is also useful in creating biphasic systems with solvents that are otherwise completely miscible with water, and can increase the upper critical solubility temperature of certain partially soluble solvents. Among the different salts used, reactions with NaCl showed the highest selectivity of 82% with 87% fructose conversion in the mixture of water and 1-butanol at 180 °C and reaction time of 8-15 min.[80]

2.2.1.2 Fructose Dehydration with Heterogeneous Catalyst

In the case of biphasic systems using heterogeneous catalysts, McNeff et al. used water-butanol system in a fixed bed catalytic reactor catalyzed by TiO_2. At 200 °C and a 3 min residence time, with the fructose concentration of 23 wt%, HMF yields were found to be lower at higher organic to aqueous phase ratio. An increase in this ratio from 0.33 to 3 (v/v), decreased HMF yield from 18 to 11%.[81]

The effects of different acid heterogeneous catalysts such as Amberlyst-15, Zeolite MOR, alumina-silicate, zirconium phosphate, alumina and niobic acid on HMF yield and selectivity in a biphasic system of water-MIBK was studied by Ordomsky et al. The catalytic activity toward production of HMF from fructose was reported in the order of Amberlyst-15 > MOR > $ZrPO_4$ > SiO_2-Al_2O_3 > Nb_2O_5 > Al_2O_3.[82] Crisci et al. also investigated the effects of different heterogeneous acid catalysts in a biphasic system with water as the reaction medium and MIBK/2-butanol (7:3 w/w) as the extraction solvent for the production of HMF from 30 wt% of fructose. They tested Amberlyst-70, SBA-15, Taa-A380 and Taa-SBA-15 at 11 wt% loading and reaction temperature of 180 °C. The highest HMF yield of 58% with 67% selectivity was obtained using Amberlyst-70 at a 10 min reaction time.[83]

Yang et al. reported the conversion of fructose to HMF by using a hydrate niobium pentoxide ($Nb_2O_5.nH_2O$) at 160 °C in water/2-butanol biphasic system. They investigated the effects of catalyst loading and reaction temperature on conversion of fructose to HMF. Fructose conversion was found to increase from 90% to 96% when the catalyst dosage was increased from 0.1 g to 0.3 g while the HMF yield decreased from 89% to 65%. This was attributed to the accelerated decomposition of HMF at high dosage of catalyst due to the availability of the much more acidic sites and production of by-products such as levulinic acid. The HMF yield and selectivity showed a positive relation to the reaction temperature and increased at higher temperatures. The highest HMF yield of 89% and fructose conversion of 90% was obtained with 0.1 g catalyst at 160 °C. The catalyst reusability and stability was tested for fructose dehydration and the results showed that the catalyst retained good activity for HMF yield and selectivity after being used seven times at 160 °C for 180 min reaction time.[21]

2.2.1.3 Fructose Dehydration in Continuous Process

Kuster and van der Steen used water and MIBK as a biphasic system for HMF synthesis from fructose. They performed their experiments in a continuous stirred tank reactor (CSTR) and used phosphoric acid (H_3PO_4) as homogeneous catalyst. They investigated the effects of different operating parameters such as temperature, fructose concentration, residence time, catalyst loading and the ratio of organic to aqueous phase on the HMF selectivity and yield. As a general trend, high temperature and increased catalyst loading enhanced HMF yield, but did not have a significant effect on selectivity. At 180 ºC and 3 min residence time, with fructose concentration of 18 wt% and organic to aqueous phase ratio of 1 (v/v), HMF yield increased from 19% to 51% and the selectivity increased from 62% to 68% when the catalyst loading changed from 5 mol% to 50 mol%. In a similar reaction conditions with 5 mol% loading of H_3PO_4, an increase in HMF yield from 19% to 48% was observed when temperature was raised from 180 to 213 ºC. Selectivity was not considerably influenced by the change in temperature and it only increased from 62% to 66%. Also in a similar condition with 10 mol% loading of H_3PO_4 at 190 ºC and 5 min residence time, by changing the organic to aqueous phase ratio from 3.5 to 7.5 (v/v), an increase in HMF yield from 55% to 69% was reported.[77]

Brasholz et al. investigated HMF formation from dehydration of fructose by using a biphasic solvent system of 0.25 M aqueous HCl and MIBK in a micro-continuous flow reactor. The best result was obtained at 140 ºC and a reaction time of 15 min when the ratio of organic to aqueous phase was 3 (v/v). Under these operating conditions 74% HMF was produced from 10 wt% fructose with less than 3% of other side products.[84]

2.2.2 Glucose Dehydration

2.2.2.1 Glucose Dehydration with Homogeneous Catalyst

De et al. studied dehydration of glucose in a biphasic system consisting of water-MIBK (1:2 v/v) and a homogeneous $AlCl_3$ catalyst (50 mol%). With a 5 wt% glucose concentration and at 130 ºC (using microwave irradiation) and a 5 min reation time, a 43% isolated HMF yield was reported. Compared to the other experiment performed by these authors, which was already reported for glucose dehydration in aqueous single phase media, the HMF yield was increased slightly from 40% in a single phase system to 43% in a biphasic system. It should be noted that in the water-MIBK system the temperature was 10 ºC higher while the reaction time was 15 min less than the aqueous phase system.[85]

In a work conducted by Chheda et al., water-DMSO (1:1 w/w) was used as a reaction solvent and MIBK/2-butanol (7:3 w/w) was used as an extraction solvent. With the organic to aqueous phase ratio of 2 (w/w), using HCl (pH=1) as a homogeneous catalyst and a glucose concentration of 10 wt%, the HMF yield of 24% with selectivity of 47% was reported at 170 ºC and 17 min reaction time.[7]

De et al. studied the effects of $AlCl_3$ for production of HMF from glucose in water-MIBK biphasic system under microwave irradiation. HMF yield of 43.7% was obtained at 130 ºC for 5 min. The high HMF yield was attributed to the driving force of the biphasic mixture in which HMF accumulates in the organic phase after being formed in the aqueous phase. $AlCl_3$ was found to be an excellent catalyst for the rapid conversion of glucose to HMF.[85]

Conversion of glucose to HMF in the presence of mineral acids as homogenous catalysts was studied by Chheda et al. at 170 ºC. It was found that in the presence of HCl addition of an extracting solvent such as MIBK/2-butanol to water enhanced the HMF selectivity to 28% compared to 11% in pure water. An efficient HMF recovery was also achieved by extracting 82% of HMF into the organic layer for subsequent isolation. Moreover, addition of DMSO along with the extracting solvent increased the rate of dehydration and improved selectivity to 53% accompanied by 22.8% HMF yield.[7]

2.2.2.2 Glucose Dehydration with Heterogeneous Catalyst

Yang et al. studied the conversion of glucose into HMF using niobic acid as the solid acid catalyst in water/2-butanol biphasic system. The catalyst was treated with phosphoric acid and calcined at 300 ºC. It was found that the acidic properties and catalytic activity of niobic acid for the dehydration was remarkably enhanced by the treatment and calcination. The highest yield and selectivity was 49% and 72%, respectively, at 160 ºC and 110 min of reaction time. Compared with fructose as reactant, the reaction time of the highest HMF yield from glucose was longer (110 min compared to 50 min), but the yield (49%) was lower than that of fructose (89%). This was mentioned to be due to the fact that glucose as aldohexose is more difficult to convert, or that when glucose was used as a reactant, isomerization into fructose firstly occurred, then dehydration to HMF. The effects of reaction time from 30 to 130 min on glucose selectivity showed an increasing trend with increasing reaction time and then reduction after 110 min, suggesting that glucose was first converted to unknown intermediates and the intermediates subsequently converted to HMF and by-products. Moreover, small amount of isomerization products were observed, indicating that isomerization reactions also occurred.[21]

Dehydration of glucose with the combination of Tin-Beta zeolites acid catalysts in water/THF or water/1-butanol biphasic system was investigated by Nikolla et al. They reported higher glucose conversion and HMF selectivity with using biphasic system compared to the single aqueous phase which was attributed to the extraction of HMF from aqueous phase and thus suppressing further degradation of HMF into undesirable by-products. Addition of an inorganic salt such as NaCl to the aqueous phase of the biphasic system increased HMF selectivity and did not affect the activity of the Sn-Beta catalyst even in high salt concentration, suggesting that the inorganic salts contribute to the extraction of HMF from aqueous to the organic phase with minimal involvement in catalyzing the reaction. The activity of Sn-Beta was not also affected by the presence of HCl. HMF selectivity and glucose conversion were found to be 55% and 75%, respectively at 160 °C and 90 min in water/1-butanol biphasic system with Sn-Beta/HCl catalyst. The selectivity and conversion increased to 72% and 79%, respectively at 180 °C and 70 min when the biphasic system was changed to water-THF.[86]

2.2.2.3 Glucose Dehydration in Continuous Process

McNeff et al. investigated the catalytic conversion of glucose to HMF in a continuous flow reactor with a fixed bed of TiO_2 and ZrO_2. The reaction with water/n-butanol solvent mixture (ratio of 1:1) at 200 °C, 2000 psi and a 3 min contact time in the presence of TiO_2 as the catalyst resulted in only a 13% HMF yield using a 23 wt% glucose concentration. Due to the poor performance of butanol, another organic solvent was considered as the extraction solvent (i.e., MIBK). With the same initial concentration of glucose and same catalyst at a lower temperature (180 °C), pressure (500 psi) and residence time (2 min), a higher HMF yield of 29% was achieved using organic to aqueous phase ratio of 10:1. This yield was decreased to 26% when the initial concentration of glucose increased to 50 wt% under pressure of 1000 and 2000 psi. However, by adding HCl to water (0.15 M), this yield increased to 37%. They also reported that under the same operating conditions, TiO_2 yielded more HMF than ZrO_2.[81]

Brasholz et al. studied HMF synthesis through dehydration of glucose in a biphasic continuous flow reactor. The reactions were performed with water/dichloromethane (CH_2Cl_2) or water/1,2-dichloroethane (DCE) as biphasic solvents in the presence of HCl. Compared to using fructose as the reactant, glucose was found to need longer periods of time or higher temperatures to improve conversion. The reactions with water/dichloromethane and water/DCE resulted in 80% and 58% yield 5-chloromethyl furfural (CMF) at 100 and 120 °C, respectively. No HMF was observed in this reaction.[84]

2.2.3 Disaccharides and Polysaccharides Dehydration

The conversion of cellobiose and sucrose disaccharides to HMF was studied by Lima et al. in a water-toluene (2.3 v/v) biphasic system. In the presence of 200 wt% aluminium-containing mesoporous TUD-1 (denoted as Al-TUD-1, Si/Al=21) as the heterogeneous catalyst, at 170 °C and with a 6 hr reaction time, 17% and 12% HMF yields were reported from a very dilute feedstock (3 wt% initial concentration) of sucrose and cellobiose, respectively. Full substrates conversion was achieved under these operating conditions.[87]

McNeff et al. reported the dehydration of cellulose and starch polysaccharides in a water-MIBK two-phase flow process using TiO_2 as the heterogeneous catalyst. A 15% HMF yield was reported from a 5% starch solution at 180 °C and a 2 min reaction time with an organic to aqueous phase ratio of 10 (v/v). Cellulose dehydration was performed in the same system by using hot extraction of solid cellulose. In this case solid cellulose was in contact with hot water in a solubilization chamber before entering the reactor. A 30% HMF yield with 34% selectivity was reported when the organic to aqueous phase ratio was 5 (v/v).[81]

An overview of HMF formation in biphasic systems shows that, although different solvents were used for extraction, the majority of them were MIBK and n-butanol. Compared to single phase systems, the HMF selectivity was greater in biphasic solvent media.

A summary of the previous works on carbohydrates dehydration to HMF in biphasic systems is listed in Table 2.3.

Table 2.3: Summary of the literature review on HMF synthesis in biphasic systems

Feed	Catalyst	Solvent	Temperature (°C)	Reaction Time	Conversion (%)	Yield (%)	Ref.
Homogenous Catalyst							
Fructose	HCl	Water/1-Butanol	150	35 min	73	58.4	80
Fructose	HCl	Water/2-Hexanone	150	35 min	97	67.9	80
Fructose	HCl	Water/1-Butanol	180	8 min	87	54.9	80
Glucose	$AlCl_3$/HCl	Water/2-Sec-Butylphenol	170	40 min	91	61.8	88
Glucose	$AlCl_3$	Water/MIBK	130	5 min	-	43.7	41
Fructose	$AlCl_3$	Water/MIBK	130	5 min	-	61.0	41
Glucose	HCl	MIBK-Butanol/Water-DMSO	170	10 min	43	22.8	89
Fructose	HCl	MIBK-Butanol/Water-DMSO	170	4 min	95	84.5	89
Sucrose	HCl	MIBK-Butanol/Water-DMSO	170	5 min	65	50.1	89
Starch	HCl	DCM/Water-DMSO	140	11 hr	91	36.4	89
Fructose	$Ba(OH)_3$	Water/MIBK	150	90 min	92	60	90
Glucose	$Ba(OH)_3$	Water/MIBK	150	5 hr	41	14	90
Heterogeneous Catalyst							
Glucose	Sn-Beta/HCl	Water/THF	180	70 min	79	56.8	86
Cellobiose	Sn-Beta/HCl	Water/THF	180	4060 min	36	12.9	86
Starch	Sn-Beta/HCl	Water/THF	180	4060 min	75	51.7	86
Fructose	$Ag_3PW_{12}O_{40}$	Water/MIBK	120	60 min	82.8	77.7	23
Glucose	$Ag_3PW_{12}O_{40}$	Water/MIBK	130	4 hr	89.5	76.3	23
Fructose	H-Mordenites	Water/MIBK	165	30 min	54	49.7	6

Fructose	SBA-15 Silica based	MIBK/2-Butanol	180	30 min	66	48.8	[91]
Fructose	Amberlyst 70	MIBK/2-Butanol	180	10 min	86	57.6	[91]
Glucose	$AlCl_3$/HCl	Water/2-Sec-Butylphenol	170	-	88	62	[88]
Glucose	Zirconium MCM-41 Silica	Water/MIBK	175	150 min	82	23	[92]
Fructose	Mesoporous AlSBA-15	Water/MIBK	165	1 hr	59	51.9	[93]
Fructose	$Nb_2O_5.nH_2O$	Water/2-Butanol	160	50 min	90	89	[21]
Inulin	$Nb_2O_5.nH_2O$	Water/2-Butanol	160	140 min	86	54	[21]
Glucose	$Nb_2O_5.nH_2O$	Water/2-Butanol	160	110 min	68	49	[21]
Continuous Process							
Fructose	H_3PO_4	Water/MIBK	190	5 min	94	69	[77]
Glucose	TiO_2	Water/n-butanol	200	3 min	-	13	[81]
Fructose	TiO_2	Water/n-Butanol	200	3 min	-	18	[81]
Glucose	TiO_2	Water/MIBK	180	2 min	-	29	[81]
Glucose	TiO_2/HCl	Water/MIBK	180	2 min	-	37	[81]
Cellulose	TiO_2	Water/MIBK	180	2 min	80	35	[81]
Fructose	HCl	Water-PVP/MIBK-Butanol	180	3 min	90	69.3	[94]
Fructose	Ion-Exchange Resin	Water-DMSO/MIBK-Butanol	90	8-16 hr	74	50.3	[94]
Fructose	HCl	Water/CH_2Cl_2	100	2.5 min	-	80 [a]	[84]
Glucose	HCl	Water/DCE	120	5 min	-	58 [a]	[84]
Fructose	HCl	Water/MIBK	140	15 min	-	74	[84]
Fructose	HCl	Water-DMSO/MIBK-Butanol	185	1 min	100	82	[95]

[a] 5-Chloromethyl Furfural (CMF) yield

2.3 HMF Synthesis in Ionic Liquids

Liquids that contain entirely ions are referred to as “Ionic Liquids” (ILs). They have low viscosities and are fluids at room temperature and below 96 °C. A broad range of organic compounds are soluble in ionic liquids to a considerable extent, thus lower amounts of solvent are required for a given process.[96]

However ionic liquids have some drawbacks for industrial applications. Lack of some physical parameters such as conductivity and viscosity is one of their major drawbacks for their industrial use. Another potential problem is the possibility of their discharge into the environment via wastewater since they are toxic and not environmentally safe.[97] Moreover, ionic liquids are expensive and sophisticated skills are required for employing and recycling them.

Despite these challenges, many researchers have used ionic liquids in dehydration of carbohydrates to produce HMF.[8,98–102] Some of them are summarized as follows.

2.3.1 Fructose Dehydration

Lansalot-Matras and Moreau used a hydrophilic ionic liquid, 1-butyl-3-methyl imidazolium tetrafluoroborate ($BMIM^+ BF_4^-$), and a hydrophobic one, 1-butyl-3-methyl imidazolium hexafluorophosphate ($BMIM^+ PF_6^-$), for dehydration of fructose to HMF in a micro batch reactor at 80 °C. Without using catalyst the highest HMF yield was reported to be 36% from an 8 wt% fructose concentration when $BMIM^+ BF_4^-$ and DMSO solvents were used (5:3 v/v) in a 32 hr reaction time.[103]

Wei et al. reported that although no HMF was produced from dehydration of fructose in 1-butyl-3-methyl imidazolium chloride ([BMIM]Cl) from 9 wt% fructose at 80 °C and a 3 hr reaction time without catalyst, increasing the temperature to 100 °C resulted in 28% HMF with 46% selectivity. This group also investigated the effects of adding a homogeneous catalyst to the solution and reported the formation of HMF at increased temperatures. At 80 °C and with a 3 hr reaction time, 22% HMF with 44% selectivity was produced with the same initial fructose concentration when 7 mol% auric chloride acid ($AuCl_3.HCl.4H_2O$) was used as a catalyst. Increasing the temperature to 100 °C and 120 °C while maintaining the rest of operating conditions, increased the yield to 44% HMF (50% selectivity) and 48% HMF (49% selectivity), respectively.[104]

A heterogeneous catalyst has been reported to be effective in increasing the HMF production. Lansalot-Matras and Moreau studied the effects of using Amberlyst-15 as a heterogeneous catalyst. With the same fructose concentration (8 wt%) when this catalyst was used with $BMIM^+$ BF_4^- solvent at 80 °C and a 3 hr reaction time, 52% HMF was produced. Adding DMSO to the solvent (5:3 v/v) enabled the reaction to take place more rapidly and produced 75% HMF yield at 100 wt% catalyst loading and 32 hr reaction time. They also demonstrated that under the same operating conditions, 87% HMF was produced when the catalyst loading increased to 200 wt%.[103]

2.3.2 Glucose Dehydration

Zhang et al. studied the ionic-liquid-mediated dehydration of glucose to HMF by Cr^{II} and Cr^{III} chlorides as homogeneous catalysts. They reported that Cr^{III} showed a higher activity and HMF selectivity than Cr^{II}. They used 1-ethyl-3-methyl imidazolium chloride as the ionic liquid. The highest HMF yield at 100 °C and a 3 hr reaction time was 72% (74% selectivity) with a 9 wt% initial fructose concentration and a 6 mol% $CrCl_3.6H_2O$.[69]

Hu et al. studied the conversion of glucose into HMF in 1-ethyl-3-methylimidazolium tetrafluoroborate ($[EMIM]BF_4$) with a common Lewis acid $SnCl_4$ as the catalyst. They claimed that, since the catalytic system was efficient, cheap and had low toxicity, it was a good combination for HMF production from glucose. The best HMF yield reported was 53% with 55% selectivity at 100 °C and a 3 hr reaction time when a feedstock of 9 wt% initial fructose concentration and 10 mol% catalyst was used.[105]

Yuan et al. reported conversion of glucose to HMF using several ionic liquids and DMSO in the presence of $CrCl_2$ or $CrCl_3$ with inexpensive co-catalysts. By using DMSO and tetraethyl ammonium chloride (TEAC) as an ionic liquid, the highest HMF yield was 54.8% with the $CrCl_2$ catalyst under mild operating conditions (120 °C and 1 hr reaction time). [76] Like Lansalot-Matras and Moreau [103], Yuan et al. also found that reactions were faster in ionic liquids than in DMSO solvent. They also claimed that $CrCl_2$ was more effective than $CrCl_3$ for the conversion of glucose to HMF in either DMSO or ionic liquids.[76]

2.3.3 Disaccharides and Polysaccharides Dehydration

Moreau et al. examined the dehydration of sucrose to HMF using 1-H-3-methyl imidazolium chloride ($HMIM^+Cl^-$) at 90 ºC. They claimed that high yields in HMF were obtained at relatively low temperatures and short reaction times. The maximum HMF yield of 52% with 50% selectivity was obtained at 90 ºC for 0.5 hr reaction without catalyst.[106]

Tao et al. studied hydrolysis of cellulose over 1-(4-sulfonic acid) butyl-3-methylimidazolium hydrogen sulfate ($[C_4H_8SO_3HMIm]\ HSO_4$) with and without presence of different catalysts such as $Mn(CH_3COO)_2$, $Mn(H_2PO4)_2$, $Mn(NO_3)_2$, $MnCl_2$ and $MnSO_4$. Without catalyst, at 150 ºC for 5 hr reaction 15% HMF with 21% selectivity was produced. The yield increased to 27-37% under the same operating conditions when 6.5 mol% of the catalysts were used. In general, the HMF yield and selectivity was raised to around 40% but it was not much influenced by the type of catalyst. The best results were obtained in the presence of $MnCl_2$ producing 37% HMF yield and 42% selectivity.[107]

Generally speaking, using ionic liquids as the reaction media and catalysts has many beneficial effects, e.g., reduced formation of levulinic acid during the process, which shows that ionic liquids could stabilize the formed HMF. However, it is difficult to separate the HMF from ionic liquids and large amounts of extracting solvents are required. Another problem is their high cost, which requires effective recycling of the ionic liquids. The problem is more serious when using untreated biomass due to the possible contamination of the liquids by the organic and inorganic impurities.[1]

2.4 Summary of Literature Review and Knowledge Gaps

The literature review can be summarized as follows:

- ➢ The main reason for selecting water as the solvent in the dehydration reactions is due to the high solubility of sugars in water. Moreover, water is considered as the cheapest and greenest solvent with abundant supply and can be used as an environmentally friendly medium.

- The yields of HMF in water are relatively low and also it is difficult to extract HMF from the water phase due to its high water solubility.
- There is no clear trend in the yields reported from homogeneous and heterogeneous catalysts. However, it is obvious that in the absence of catalyst lower yields of HMF are obtained.
- In order to achieve a higher selectivity, the rehydration reactions of HMF in aqueous phase should be suppressed by either stabilization or removing HMF from the reaction environment.
- Although previous works declare that fructose (ketose) is much more reactive and selective toward HMF than glucose (aldose), the use of glucose as the feedstock for bulk production of HMF is considered more cost-effective because glucose is much cheaper and more readily available in the nature than fructose.
- HMF selectivity and yield from glucose is less than that from fructose under the same reaction conditions (i.e., fructose is much more readily converted to HMF than glucose). This can be attributed to the isomerization step of glucose to fructose as well as the abundance of acyclic fructose compared to acyclic glucose and more stable ring structure of glucose.
- Isomerization of glucose to fructose as an intermediate step for production HMF is of great importance.
- The isomerization process is accompanied by production of a variety of by-products. Thus a highly selective, efficient and inexpensive catalyst is essential to control the undesirable reactions and improve the reaction kinetics.
- Despite the most research efforts towards HMF production from edible carbohydrates such as glucose and fructose, using inedible resources such as lignocellulosic biomass as starting material would be preferable. Therefore, the development of efficient routes for converting inedible biomass into HMF is essential for achieving sustainable production of HMF.
- The HMF produced by the dehydration of fructose in aqueous medium, could further rehydrates to produce levulinic and formic acids. The most popular approach to prevent

this sequential reaction and improve HMF yield is using organic solvents as the reaction media.

- Literature shows that the HMF yields and selectivity were much higher in organic solvents than those in aqueous solutions.
- An effective and alternative method to prevent the further rehydration of produced HMF to levulinic and formic acids and thus increase the HMF yields is removal (extraction) of HMF from the reaction mixture by either using an extracting solvent or a selective adsorbent (e.g., activated carbon).
- MIBK has been widely used as an extractive solvent for fructose dehydration. It has been considered as a good solvent for sugars dehydration in water that could suppress the undesired side reactions and extract more HMF into organic phase.
- An overview of HMF formation in biphasic systems shows that, although different solvents were used for extraction, the majority of them were MIBK and n-butanol. Compared to single phase systems, the HMF selectivity was greater in biphasic solvent media.
- Using ionic liquids as the reaction media and catalysts has many beneficial effects, e.g., reduced formation of levulinic and formic acids during the process, which shows that ionic liquids could stabilize the formed HMF. However, they are expensive and sophisticated skills are required for employing and recycling them.

So far, a number of studies have been conducted for the synthesis of HMF by conversion of a wide variety of biomass-based feedstocks (e.g., monosaccharides, disaccharides and polysaccharides) in different media (e.g., aqueous, organic, biphasic, ionic liquid), using various catalysts (e.g., homogeneous, heterogeneous, acidic, basic), under various reaction conditions (e.g., temperature, pressure, reaction time, initial concentration of substrate, catalyst loading, solvents ratio) and different reactor configurations (e.g., batch, continuous). However, cost-effective production of HMF in a large scale for bulk production of fuels and chemicals has not been yet realized. As such, there is a great interest to develop an economically viable process to produce HMF from biomass in a large industrial scale. The literature review shows that a high isolated HMF yield can be obtained from high cost processes (e.g., organic solvent, expensive catalyst and media such as ILs, high temperature, complex separation procedure, expensive equipment, etc.), while low cost processes lead to a low isolated HMF yield. It is highly desirable to develop inexpensive processes using low-cost catalyst and media with high HMF selectivity and yield. The other issue for the existing HMF synthesis processes is their potential for scale up, associated with reactor design and configuration. Generally, for large industrial scale production, a continuous-flow process using heterogeneous catalyst is preferable due to the ease of catalyst separation and recycling as well as capability of varying the reaction time and thus altering the product selectivity. However, there is only limited research on HMF synthesis using continuous reactors with heterogeneous catalysts. Therefore, more comprehensive studies are still needed to investigate the feasibility of cost-effective HMF production in continuous-flow reactor using inexpensive heterogeneous solid catalyst and optimize the operating conditions for the maximum HMF selectivity and yield.

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Chapter 3

3 Catalytic Isomerization of Glucose to Fructose using Heterogeneous Solid Base Catalysts in a Continuous-Flow Tubular Reactor: Catalyst Screening Study

Abstract

Isomerization reactions of glucose into fructose in hot compressed water were studied in a continuous-flow tubular reactor using different heterogeneous base catalysts. The activities of solid base catalysts including calcined-rehydrated hydrotalcite, magnesium oxide, Amberlyst A21 ion exchange resin and two commercial hydrotalcite catalysts (PURAL MG30 and PURAL MG30/K_2CO_3) were compared. The most active catalyst was found to be magnesium oxide, which showed the highest glucose conversion (36.3%) and highest fructose yield (22.8%) at 100 ºC. Calcined-rehydrated hydrotalcite exhibited over 78% fructose selectivity at 100 ºC which was the highest value compared to the other catalysts. The effects of reaction temperature were studied on the activity of hyrdotalcite and magnesium oxide catalysts. Increasing the reaction temperature had a positive effect on glucose conversion and fructose yield for both catalysts and resulted in fructose yields of 19.5% and 25.1% at 120 ºC for hydrotalcite and magnesium oxide, respectively. The effects of calcination temperature on the catalytic activity of hydrotalcite were also tested at two different temperatures. Calcination temperature of 450 ºC was found to be more effective than 350 ºC to improve the catalytic activity of this catalyst for glucose isomerization reaction. The stability of the hydrotalcite and magnesium oxide catalysts with time was also investigated. Little drop in conversion was observed for both catalysts and the fructose yield remained almost constant during 4 hours of continuous time on stream.

Keywords: Glucose, Isomerization, Fructose, Continuous-flow tubular reactor, Magnesium oxide, Hydrotalcite, Catalyst characterization, Catalyst stability

3.1 Introduction

Glucose is a simple sugar and the monomer unit of cellulose and is likely to become one of the most important starting chemicals for bulk production of renewable biofuels and biomaterials due to the increased dependency of society on sustainable and renewable energy and chemical production.[1,2] Thus, a fast and highly selective process for glucose conversion to value added chemicals is of great interest. Hot compressed water (HCW) has been considered as a reaction medium for glucose conversion due to its low price and environmentally benign characteristics. The primary reactions of glucose in hot compressed water can be classified as (1) isomerization of glucose to fructose, (2) dehydration of glucose to 1,6-anhydroglucose (AHG) and dehydration of fructose to 5-hydroxymethyl-2-furaldehyde (HMF) and (3) retro-aldol condensation of fructose to glycolaldehyde and dihydroxyacetone, etc.[3]

Catalytic conversion of glucose into fructose through isomerization as an intermediate step for the production of valuable furan derivatives and platform chemicals has attracted great interests.[4,5] Since this reaction is normally accompanied by a variety of by-products, it is important to control the operating conditions such as temperature, reaction time and initial concentration of feedstock in order to avoid the undesirable reactions and to improve the reaction kinetics. An efficient catalyst can also affect the glucose isomerization reaction. It has been reported that at a low temperature, the glucose isomerization reaction could be catalyzed by base catalysts.[2,3] So far, different types of homogeneous and heterogeneous catalysts have been tested in this process. Generally, heterogeneous or solid catalysts are more advantageous compared to homogenous ones due to their lower impact on the operating equipment and systems and global environment and their potential for recycling and reusability. They will also facilitate large-scale industrial operations.[3,6]

A number of researchers have studied the performances of metal oxides as heterogeneous catalysts for glucose isomerization reaction. For example, Watanabe et al. studied the catalytic activity of ZrO_2 and TiO_2 (rutile and anatase) at 200 °C of reaction temperature and 5 min reaction time.[1,3] They reported enhanced conversion rate in the presence of anatase TiO_2. They also compared the performance of these metal oxides with homogeneous acid and alkali catalysts (NaOH and H_2SO_4 solutions) and reported the highest conversion of about 80% with anatase TiO_2. No considerable effect was observed with NaOH and rutile TiO_2 and fructose formation was inhibited by H_2SO_4.[1] Cation-exchanged A, X, Y zeolites and hydrotalcites were studied by Moreau et al. at 95 ºC for isomereization of glucose to fructose.[7] Among the catalysts used, Ca- and Ba-exchanged A, X and Y zeolites were found to be less selective, whereas those with a moderate basicity such as NaX and KX showed fructose selectivity of about 90%. However, the high fructose selectivity was only obtained at glucose conversions lower than 25%. The hydrotalcite samples were found to be less selective than cation exchanged zeolites due to their relatively stronger basic properties.

The effects of operating conditions on glucose isomerization were also studied by some researchers. Souza et al. conducted experiments with 10 mol%/glucose of NaOH as homogenous catalyst at 40-80 ºC and 15 min reaction time.[8] They found that there was an optimum temperature for the highest fructose yield. Increasing temperature from 40 to 80 ºC enhanced the glucose conversion followed by a continuous drop in fructose yield for temperatures above 50 ºC. They also reported that glucose conversion increased with increasing reaction time from 0 to 60 min but fructose yield was higher for short reaction times (10-15 min). They tested other catalysts such as ZrCs, which is a strong solid base, and some synthesized mesoporous ordered molecular sieves from the M41S family, and found that the hybrid solid base catalysts were much more active than ZrCs for isomerization of glucose to fructose. The best result was obtained with [CTA] Si-MCM-50 at 100 ºC and 2 hours of reaction time, being 22% glucose conversion and 17% fructose yield. Investigation on the effects of reaction conditions was also performed by Yue et al., who studied isomerization of glucose to fructose at 100 ºC and reaction times from 0 to 180 min with layered zirconosilicates as heterogeneous catalysts.[9] With the reaction time of 30 min, the glucose conversion was 60% with 26% fructose yield. Increasing the reaction time resulted in a slight increase in glucose conversion and little change in fructose yield.

So far, almost all studies on the catalytic glucose isomerization reaction have been performed in batch reactors and little attention has been paid to continuous-flow reactors, which are more desirable for large industrial scale and commercial production. They also have the capability of varying the reaction time and thus altering the product properties by changing the feeding flow rate and/or catalyst loading.

In the present work, isomerization of glucose to fructose in a continuous-flow tubular reactor designed and constructed in-house by the authors was investigated. Catalyst screening study was first performed to compare the activities of different heterogeneous solid base catalysts including magnesium oxide (MgO), calcined-rehydrated hydrotalcite (HT-C-R), Amberlyst A21 (Amb. A21), and two commercial hydrotalcite catalysts (HT MG30 and HT MG30/K_2CO_3). The effects of reaction temperature on the activity of hydrotalcite and magnesium oxide catalysts as well as the effects of calcination temperature on the catalytic activity of hydrotalcite were studied. To the best of our knowledge, no work has been reported on isomerization of glucose to fructose with those catalysts in a continuous-flow tubular reactor. Characterization of the catalysts was performed through thermogravimetric analysis (TGA) for thermal stability of the catalyst structure, X-ray diffraction (XRD) for crystalline phase and structure of the catalyst, Brunauer-Emmett-Teller (BET) for surface area as well as pore size distribution (PSD) of the catalyst surface and Fourier transform infrared (FT-IR) spectrometry for functional groups of the catalyst.

3.2 Materials and Methods

3.2.1 Materials

D-(+)-glucose (>99.5%), synthetic hydrotalcite (i.e., magnesium aluminum hydroxyl carbonate, $Mg_6Al_2(CO_3)(OH)_{16}.4H_2O$, Mg/Al molar ratio of 3:1), magnesium oxide (beads -30 mesh) and Amberlyst A21 were purchased from Sigma-Aldrich. Commercial hydrotalcites PURAL MG30 (HT MG30) and PURAL MG30/K_2CO_3 (HT MG30/K_2CO_3) 5×5 cylindrical tablets (MgO/Al_2O_3 ratio of 30/70) were provided by SASOL Germany GmbH. HPLC grade water for preparing the mobile phase for HPLC analyses was obtained from EMD Millipore Milli-Q water system with a resistivity of 18.2 MΩ.cm.

3.2.2 Catalyst Preparation

For activation/pelletization, synthetic hydrotalcite (HT) was first calcined at 450 ºC in a muffle furnace with the heating rate of 10 ºC/min for 10 hours (HT-C) and then rehydrated by adding deionized water after cooling inside a desiccator to form a soft paste. The paste was dried overnight in an oven at 80 ºC and then crushed by a mortar and pestle. After sieving, particles between 300-840 µm (Mesh No. 50 to Mesh No. 20) were collected for using as activated solid catalyst particles in the experiments (HT-C-R). MgO, HT MG30 and HT MG30/K_2CO_3 were crushed with a Wiley Mill, and particles between 300-840 µm (Mesh No. 50 to Mesh No. 20) were collected after sieving to be used as solid catalyst particles. Amberlyst A21 beads was used as received.

3.2.3 Continuous-Flow Reactor Setup and Experimental Procedure

The catalytic isomerization of glucose to fructose was performed in a continuous-flow tubular reactor, schematically presented in Figure 3.1. The lab-scale tubular reactor setup was designed and constructed in-house for testing different heterogeneous solid catalysts as a fixed bed within the tubular reactor for isomerization of glucose to fructose in aqueous media.

The reactor setup mainly consists of a vertical tubular reactor (SS-316 3/8” tube - 40 cm long) located within an electric cylindrical heater (Omega CRFC Series). The temperature of the flowing media inside the reactor is adjusted and controlled using a PID temperature controller (Omega CSC32) connected to the heater (output) and a thermocouple (input) placed at upstream of the reaction zone (catalyst bed) inside the tubular reactor. To achieve a uniform temperature profile inside the reactor, a specialized pre-heating feature has been devised and applied using a helical SS-316 1/16” tube, which goes up and then down along the tubular reactor inside the heater to effectively pre-heat the flowing media before entering the reactor from the bottom.

In operation, appropriate amount of heterogeneous solid catalyst (particle size between 300-840 µm) is preloaded and supported inside the tubular reactor as a packed bed between two quartz wool plugs at the middle of the reactor/heater (reaction zone). An HPLC feeding pump (Scientific Systems Inc. - Mighty Mini Pump) connected to the bottom of the tubular reactor provides adjustable upward rising flow of aqueous feedstock solution (pure glucose in deionized water) through the tubular reactor. The temperature of the flowing media after passing the catalyst bed is also monitored using another thermocouple (Omega 1/16” K-Type) located downstream of the reaction zone (catalyst bed) inside the tubular reactor and connected to a digital thermometer. The pressure of the flowing media inside the reactor is adjusted and controlled using a back-pressure regulator valve (Swagelok KBP Series) located on the exit line of the reactor and the pressure of the system is monitored with a pressure gauge.

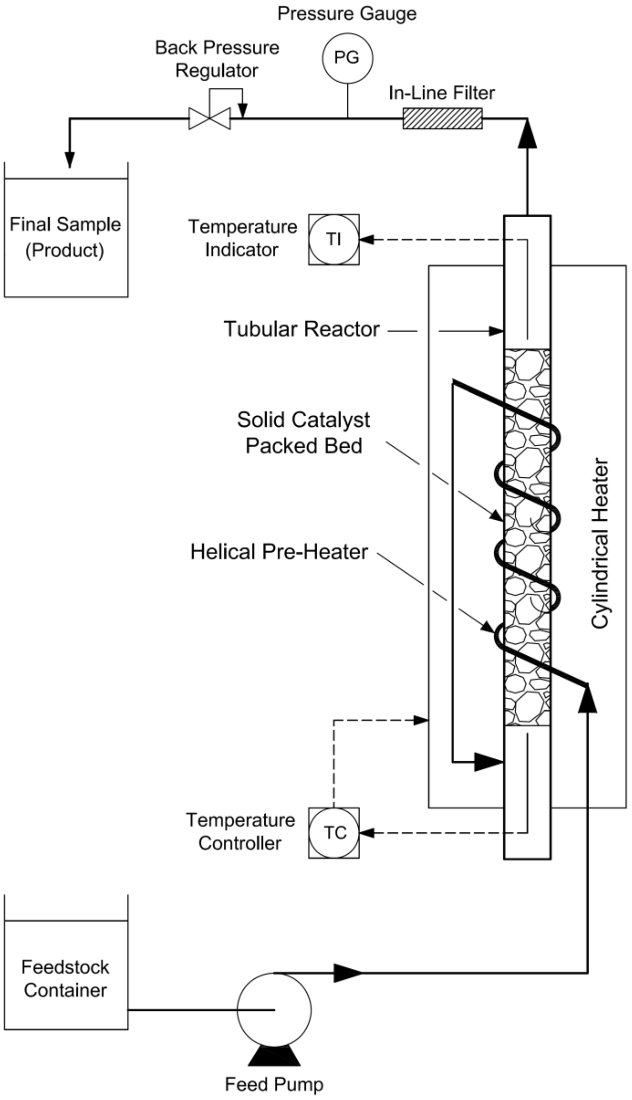

Figure 3.1: Schematic diagram of the continuous-flow tubular reactor system

In a typical run, after preloading a specific amount of the heterogeneous solid catalyst particles inside the tubular reactor as a packed bed and assembling the reactor inside the cylindrical heater, the aqueous feedstock solution was pumped into the reactor using the dedicated feeding pump at a specific flow rate. When the reactor was filled with the feedstock solution, the pressure inside the reactor was increased to the desired pressure (typically 10 bars) using the back pressure regulator valve to avoid boiling of the water at the reaction temperatures above 100 ºC and the formation of vapor bubbles within the reactor system. The reactor was then heated to the desired temperature after insulating the cylindrical heater and tubular reactor. After the reactor reached a stable temperature at the set-point and the steady state condition was achieved (depending on the feeding flow rate), samples were taken every hour, and subjected to HPLC analysis. The concentrations of glucose and fructose were calculated from HPLC chromatographs in order to determine the glucose conversion as well as fructose selectivity and yield. The time on stream (TOS) for all of the experiments was 4 hours and no detectable soluble by-product or any other intermediate was found in HPLC chromatographs.

3.2.4 Product Analyses

The product samples collected from the experiments were analyzed using an HPLC (Waters 2690 Separation Module) equipped with an RI detector (Waters 410 Differential Refractometer) with internal detector temperature of 50 ºC to determine the amount of product (fructose) produced and the amount of feedstock (glucose) consumed. Agilent Hi-Plex Pb column (9 µm, 7.7×300 mm) maintained at 60 ºC was used and the mobile phase was 100% Milli-Q HPLC grade water at a flow rate of 0.6 ml/min. The results for all experiments were analyzed by external calibration curves generated for glucose and fructose separately using standard solutions of glucose and fructose with known concentrations. The results were reported in terms of conversion, selectivity and yield, which are defined and calculated as follows:

$$\text{Glucose Conversion (\%)} = \frac{\text{Moles of glucose converted}}{\text{Initial moles of glucose}} \times 100\%$$

$$= \frac{[(C^{F}_{Glu} \times Q) - (C^{P}_{Glu} \times Q)]/M_{Glu}}{(C^{F}_{Glu} \times Q)/M_{Glu}} \times 100\% = \frac{C^{F}_{Glu} - C^{P}_{Glu}}{C^{F}_{Glu}} \times 100\% \qquad (3.1)$$

$$\text{Fructose Selectivity (\%)} = \frac{\text{Moles of fructose produced}}{\text{Moles of glucose converted}} \times 100\%$$

$$= \frac{(C_{Fru}^{P} \times Q)/M_{Fru}}{[(C_{Glu}^{F} \times Q) - (C_{Glu}^{P} \times Q)]/M_{Glu}} \times 100\% = \frac{C_{Fru}^{P}}{C_{Glu}^{F} - C_{Glu}^{P}} \times 100\% \qquad (3.2)$$

$$\text{Fructose Yield (\%)} = \frac{\text{Moles of fructose produced}}{\text{Initial moles of glucose}} \times 100\%$$

$$= \frac{(C_{Fru}^{P} \times Q)/M_{Fru}}{(C_{Glu}^{F} \times Q)/M_{Glu}} \times 100\% = \frac{C_{Fru}^{P}}{C_{Glu}^{F}} \times 100\% \qquad (3.3)$$

where,

C_{Glu}^{F} is mass concentration of glucose in the feedstock solution (mg/ml),

C_{Glu}^{P} is mass concentration of glucose in the product sample (mg/ml),

C_{Fru}^{P} is mass concentration of fructose in the product sample (mg/ml),

Q is volumetric flow rate of the feedstock solution (ml/min),

M_{Glu} is molar mass of glucose (=180.16 g/mol),

M_{Fru} is molar mass of fructose (=180.16 g/mol).

It is obvious that the combination of higher conversion (higher glucose disappearance) and greater selectivity (lower by-products formed) results in a higher yield, which is desirable.

3.2.5 Catalyst Characterization Methods

X-ray diffraction (XRD) analyses of the catalyst samples were conducted on a PANalytical X'Pert Pro diffractometer using Cu-Kα radiation.

Brunauer-Emmett-Teller (BET) surface area as well as pore volume and pore size distribution (PSD) measurements were performed on a Micrometrics Tristar II 3020 series instrument. The samples were initially degassed under nitrogen flow for 8 hours at 90 °C.

Thermogravimetric analysis (TGA) of the fresh catalysts was conducted using a PerkinElmer Pyris 1 TGA in a nitrogen atmosphere. The samples were heated in a nitrogen flow at 20 ml/min from 40 °C to 100 °C at 10 °C/min and then kept at 100 °C for 10 min to remove the adsorbed moisture and volatile compounds. Then they were heated up to 700-

800 °C at heating rate of 10 °C/min and the change in the sample weight by temperature was recorded. For the spent (used) catalyst, oxygen flow was used to burn the humins deposited on the surface of the catalysts. Derivative thermogravimetric (DTG) graphs were obtained from first derivative of TGA results with respect to time or temperature.

Fourier transform infrared (FT-IR) spectrometry analyses of the catalyst samples were conducted on a PerkinElmer FT-IR spectrometer and the spectra were recorded in the region of 4000-550 cm^{-1}.

3.3 Results and Discussion

3.3.1 Characterization of Fresh Catalysts

The XRD patterns of the catalysts are presented in Figure 3.2. Hydrotalcites are double layered hydroxides composed of MgO and $MgAl_2O_4$ and the patterns for HT-C-R, HT MG30 and HT MG30/K_2CO_3 clearly confirms the layered structure, which is consistent with the previous hydrotalcite characterization studies.[10–12] The peaks observed at 2θ = 11.6°, 23.3°, 34.7° correspond to the basal (003), (006) and (009) planes, respectively. The difference between the intensities of the reflections from one sample to another indicates different degrees of crystallinity and structure when the cationic composition or Mg/Al ratio varies.[13] The Mg/Al molar ratio of HT-C-R (3:1) is much greater than that of HT MG30 and HT MG30/K_2CO_3 (1:2), which results in higher intensities for the peaks and different basicity. The basal peaks for HT-C-R are narrower in width and higher in intensity compared to the commercial HT MG30 and HT MG30/K_2CO_3. Since the crystal size is inversely proportional to the half band width according to Scherrer's equation.[14] This indicates that the HT-C-R has more uniform crystals and larger crystal size. The peaks observed at 2θ = 39.1°, 46.4°, 60.6° and 62.1° correspond to the non-basal (015), (018), (110) and (113) planes, respectively. Magnesium oxide showed peaks at 2θ = 37.1°, 42.9°, 62.4°, 74.7° and 78.7°, which correspond to (111), (200), (220), (311) and (222) planes, respectively. The patterns are compatible with the ones previously reported in literature.[15,16] No major peaks were observed for Amberlyst A21 catalyst, indicating that this catalyst is amorphous and does not have a crystalline structure.

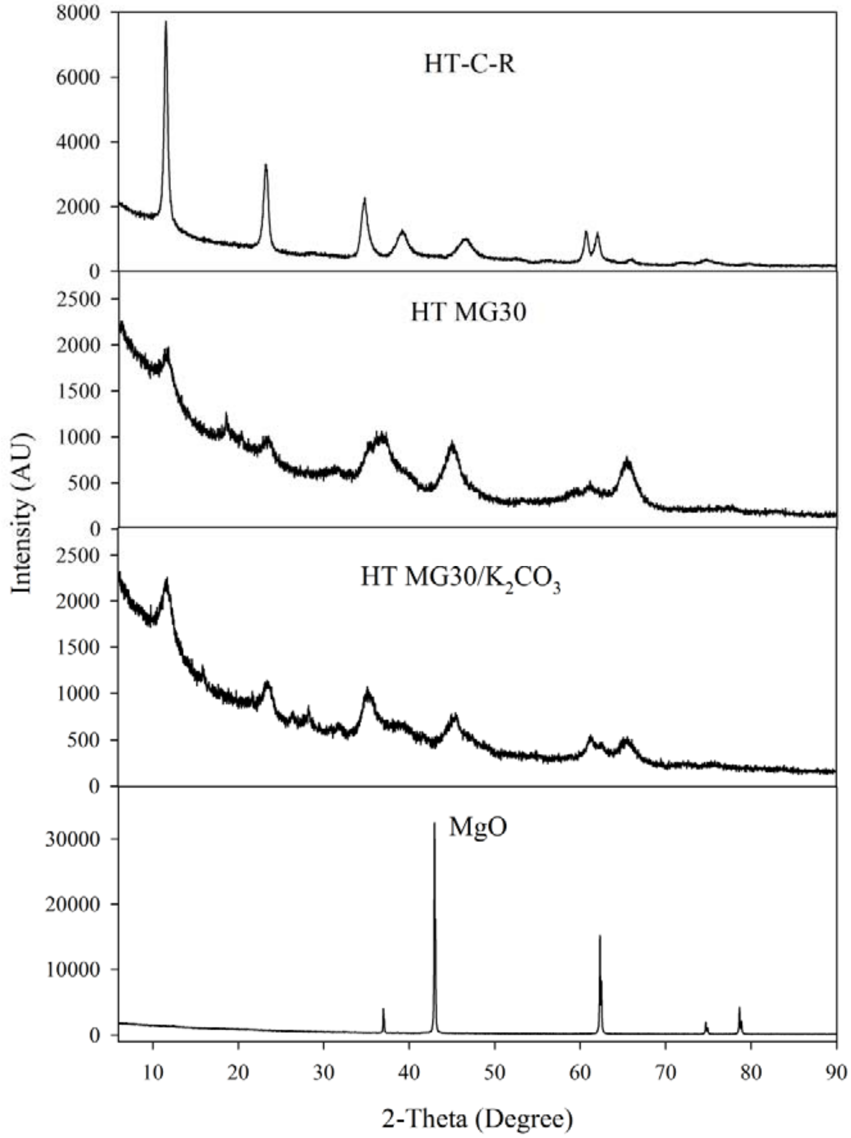

Figure 3.2: X-ray diffraction of the fresh catalysts

The results of N_2 physisorption analysis of the catalysts are summarized in Table 3.1. The two commercial HT MG30 and HT MG30//K_2CO_3 exhibited the largest surface areas and total pore volumes compared to the other catalysts tested. The surface area of HT-C-R (19 m^2/g) was much lower compared to the two commercial hydrotalcites; however, it had larger average pores diameter. MgO was found to have the smallest BET surface area of 0.2 m^2/g and total pore volume of 0.0004 cm^3/g, suggesting a nonporous structure.

Table 3.1: Textural properties of the fresh catalysts

Catalyst	BET Surface Area (m^2/g)	Average Pore Diameter (nm)	Total Pore Volume (cm^3/g)
HT-C-R	19	19	0.09
HT MG30	171	7	0.31
HT MG30/K_2CO_3	133	10	0.32
Amb. A21	33	10	0.09
MgO	0.2	7	0.0004

Thermogravimetric analysis (TGA) results for the fresh catalysts are presented in Figure 3.3. According to TGA graphs the total weight losses for HT-C-R, HT MG30 and HT MG30/K_2CO_3 are 38.5%, 19.7% and 28.4%, respectively. All three hydrotalcite catalysts show two stages of weight loss with the sharper and more distinct curves for HT-C-R than others. The first weight loss occurred between 100 and 250 ºC corresponding to the loss of interlayer water molecules and the second took place after 250 ºC, which is attributed to the removal of condensed water molecules and loss of carbonate anions via the formation of carbon dioxide from the brucite layer.[11,17,18] This could also be clearly observed in the derivative thermogravimetric (DTG) graphs of the hydrotalcite catalysts (Figures 3.4 a-c). The maximum weight loss rates for HT-C-R were greater and they occurred at higher temperatures (213 and 390 ºC) compared to other commercial hydrotalcite catalysts. The Amberlyst catalyst exhibited a large weight loss (88%) after 300 ºC, which indicates that this catalyst is mostly composed of organic compounds and is mostly decomposed with increasing temperature. The maximum weight loss rate for this catalyst was at 407 ºC (Figure 3.4 d). Figure 3.3 b shows that magnesium oxide was thermally stable and did not show any weight loss as a function of temperature as this catalyst is already a metal oxide and cannot be decomposed any further. The percentage of first and second weight loss for each catalyst is reported in Table 3.2.

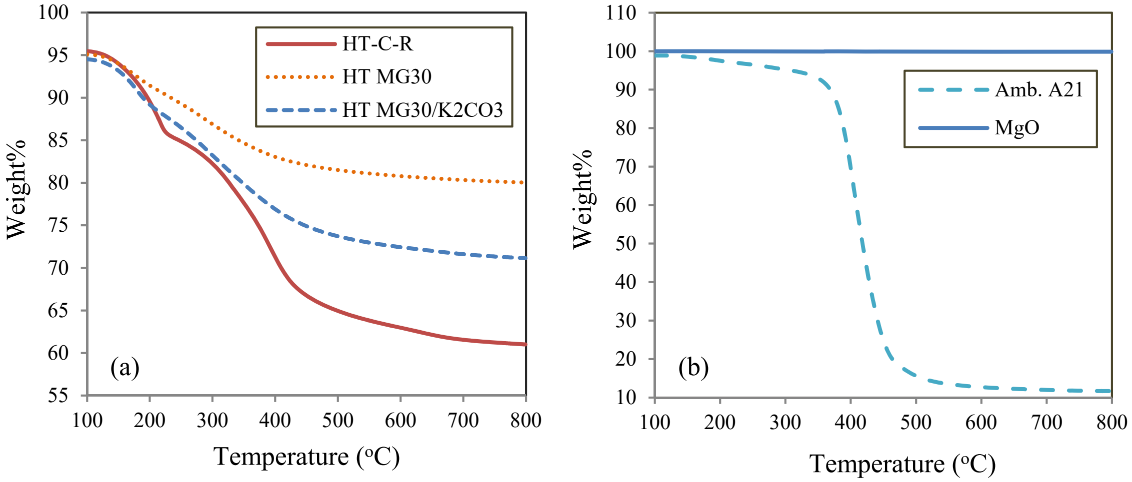

Figure 3.3: TGA graphs for the fresh hydrotalcites (a), Amb. A21 and MgO (b)

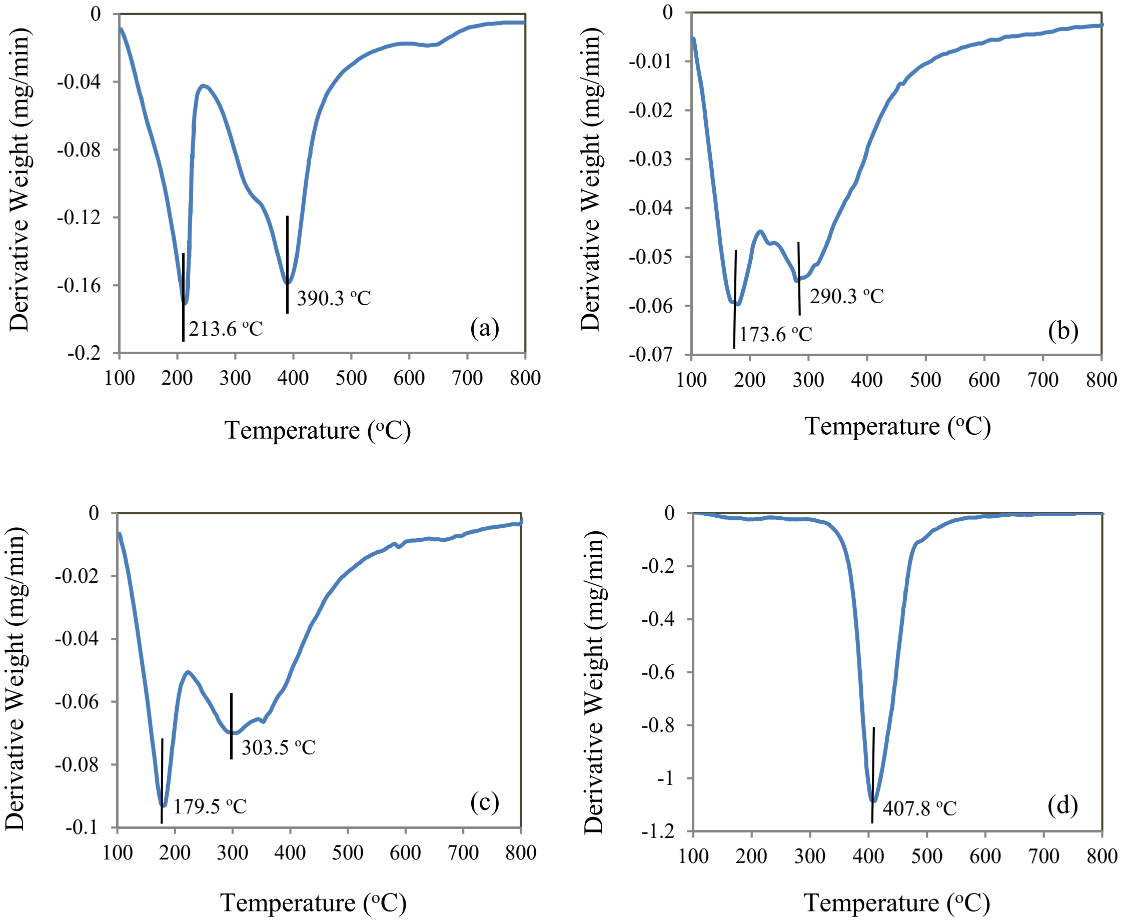

Figure 3.4: DTG graphs for the fresh HT-C-R (a), HT MG30 (b), HT MG30/K_2CO_3 (c) and Amb. A21 (d)

Table 3.2: TGA weight loss results for the fresh catalysts

Catalyst	First Weight Loss (%)	Second Weight Loss (%)
HT-C-R	15.15	23.30
HT MG30	8.57	11.10
HT MG30/K_2CO_3	10.82	17.57
Amb. A21	88.01	-
MgO	-	-

The structure of the studied catalysts was also characterized by FT-IR analysis and is presented in Figure 3.5. Hydrotalcite catalysts showed a broad absorption at around 3460 cm^{-1}, which is attributed to the O-H stretching vibration of the interlayer water molecules and hydroxyl groups in hydroxide layer of the catalyst. The intensity of this peak is stronger for HT-C-R than HT MG30 and HT MG30/K_2CO_3 indicating the presence of more water and hydroxyl groups in the hydroxide layer of this catalyst. The weak absorption at 1630 cm^{-1} is attributed to the bending vibration of water molecules in the interlayer. The sharp peak at 1370 cm^{-1} indicates the stretching vibration of carbonate anions. The FT-IR spectrum of Amberlyst A21 showed different peaks indicating the presence of a large number of functional groups in its structure. The peaks observed at around 2930 cm^{-1} were attributed to the stretching vibration of C-H (alkane) and the pair of the bands at and 2770 cm^{-1} and 2810 cm^{-1} were attributed to the stretching vibration of aldehyde C-H. The two peaks at 1450 cm^{-1} and 1369 cm^{-1} could be attributed to the bending vibration of methylene and methyl groups. The bands located between 1000 cm^{-1} and 1310 cm^{-1} were attributed to the stretching vibration of C-N. They could also represent the stretching vibration of C-O and the possible presence of esters and anhydrides. The lack of the band related to the stretching vibration of N-H in the region from 3500 to 3200 cm^{-1} suggests that Amberlyst A21 contained tertiary amine functional groups. The vibrations at 860 cm^{-1} and 800 cm^{-1} represent the bending vibration of CH out-of-plane. No major peaks in FT-IR spectrum of magnesium oxide were detected and therefore no graph is presented for this catalyst.

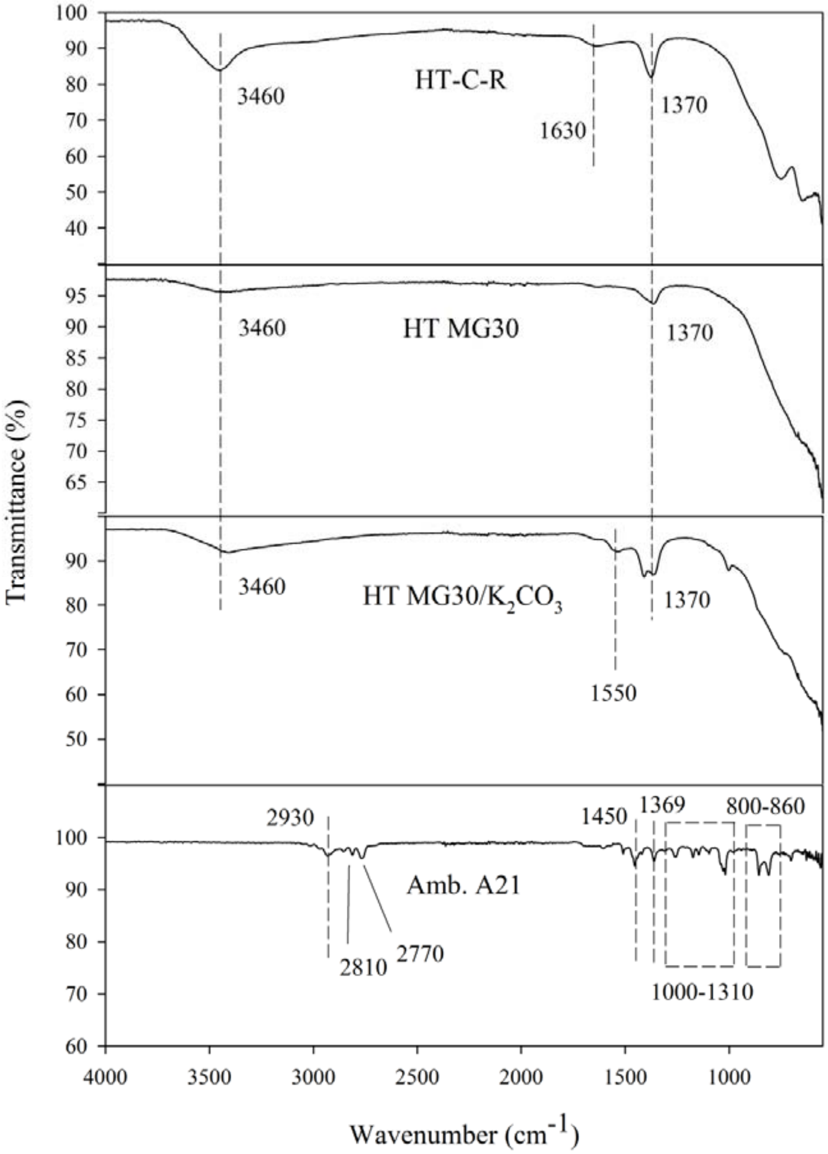

Figure 3.5: FT-IR spectra of the fresh catalysts

3.3.2 Catalytic Isomerization of Glucose to Fructose

3.3.2.1 Performance of Different Solid Base Catalysts

The results for the effects of different catalysts on glucose isomerization are presented in Figure 3.6. These samples were taken two hours after reaching steady state condition. All of the experiments were performed at 100 ºC with initial glucose concentration of 100 mg/ml, feeding flow rate of 0.5 ml/min and 4 g catalyst loading (WHSV = 0.75 hr^{-1}) and no detectable soluble by-product was found in HPLC analysis.

Comparison of the results show that MgO had the highest glucose conversion (36.3%) and fructose yield (22.8%), while the highest fructose selectivity (78.1%) was obtained by HT-C-R catalyst. The conversion, selectivity and yield in the presence of MgO catalyst and fructose selectivity and yield in the presence of HT-C-R catalyst were even higher than those of commercial HT MG30 and HT MG30/K_2CO_3 catalysts. The obtained fructose yields follow the trend of MgO > HT-C-R > HT MG30 > HT MG30/K_2CO_3 > Amb A21. Amberlyst A21 with the lowest glucose conversion of 6.4% and fructose yield of 3.8% was found to be the least effective catalyst for glucose isomerization reaction.

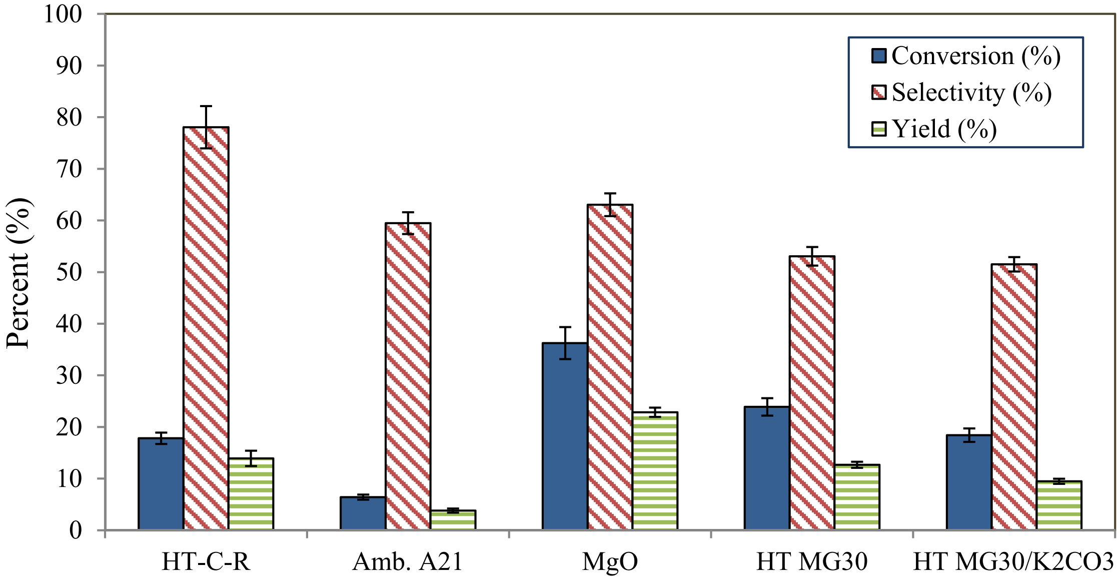

Figure 3.6: Activity of solid base catalysts tested in glucose isomerization at 100 °C (Initial glucose concentration of 100 mg/ml, feeding flow rate of 0.5 ml/min)

According to BET results (Table 3.1), MgO had the lowest BET surface area while it was the most active catalyst for this reaction in terms of glucose conversion and fructose yield. In addition, despite the large BET surface area of the commercial hydrotalcite catalysts, they did not show a superior activity in isomerization reaction. Thus, the BET surface area may not be a key indicator of the catalyst performance in glucose isomerization reaction and the activity of a catalyst is mostly determined by the type of the material which might tune the features of the accessible basic sites (number and strength).[4] The high activity of MgO in glucose isomerization reaction could be due to the unique characteristics of the strong base sites on the surface of this catalyst.[19] However, the fructose selectivity of this catalyst is still lower than that of activated hydrotalcite (HT-C-R). High fructose selectivity in the presence of HT-C-R catalyst could be attributed to the formation of abundant and selective surface base sites during the rehydration process.[12] The lowest activity for glucose isomerization reaction was observed with Amb. A21. This catalyst is an ion exchange polystyrene resin and the catalytic activity of polystyrene resins depends on their swelling property in the solvents and the solvent pH. At neutral pH, adsorption of Amb. A21 is characterized with non-ionic interactions, like hydrophobic and aromatic interactions, which result in lower adsorption capacity.[20] Thus, MgO and HT-C-R could be identified as the catalysts with highest conversion and selectivity for glucose isomerization, respectively and selected for further investigations.

3.3.2.2 Effects of Reaction Temperature

MgO and HT-C-R activities were tested at different reaction temperatures and the results are presented in Figure 3.7.

For both catalysts, glucose conversion and fructose yield improved with increasing reaction temperature while the fructose selectivity dropped. Conversion and selectivity were found to be more sensitive to the reaction temperature for MgO catalyst. The fructose selectivity for HT-C-R remained almost constant with a slight increase from 72.3 at 80 ºC to 78.1% at 100 ºC. The decrease in selectivity indicates the formation of by-products, mostly insoluble humins as a result of self-polymerization and condensation of glucose and fructose by increasing temperature. Therefore, it could be concluded that even at higher temperatures less undesirable products were formed when HT-C-R was used as a catalyst compared to MgO. Fructose yield was enhanced for both catalysts as a result of temperature rise and reached a maximum of 19.5% for HT-C-R and 25.1% for MgO at 120 ºC. This is a considerable fructose yield in continuous mode using heterogeneous catalyst. Further increase in temperature to 140 °C for HT-C-R was also studied. At this temperature glucose conversion increased to 41.9% (28.2% at 120 °C), but fructose selectivity dropped to 47.6% (68.9% at 120 °C), and no enhancement in fructose yield compared to the one at 120 °C was observed. Thus, 80-120 °C seems to be a good range of reaction temperature for fructose production using HT-C-R catalyst because of the higher selectivity.

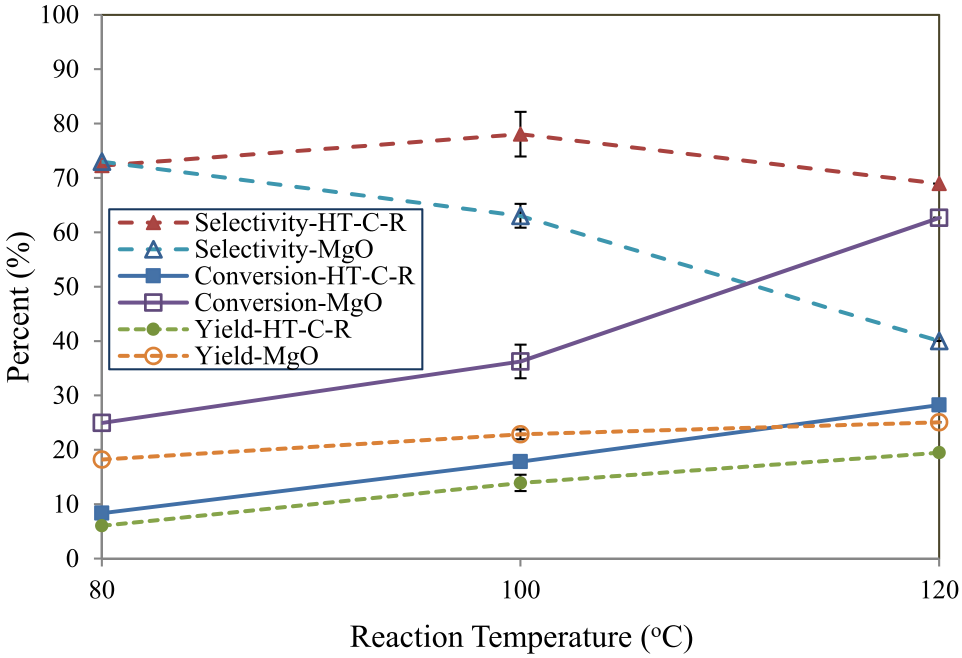

Figure 3.7: Effects of reaction temperature on the activity of HT-C-R (closed symbols) and MgO (open symbols) catalysts in glucose isomerization (Initial glucose concentration of 100 mg/ml, Feeding flow rate of 0.5 ml/min)

3.3.2.3 Effects of Calcination Temperature on Hydrotalcite Catalytic Activity

As HT-C-R catalyst showed more than 70% fructose selectivity in the experiments, the possibility of enhancing its catalytic activity for glucose isomerization reaction was evaluated by studying the effects of calcination temperature as the first step in its activation process. Calcination temperature of hydrotalcite is known to affect the catalytic activity of this catalyst as it effectively destroys the hydrotalcite structure.[10,21] Hydrotalcites are usually calcined at temperatures between 300-500 °C.[10] In order to determine the effects of this parameter, hydrotalcite was activated at two different temperatures of 350 °C and 450 °C and rehydrated as already described in the materials and methods section. It was then used in the continuous-flow reactor at the reaction temperature of 110 °C for isomerization of glucose to fructose. The results are shown in Figure 3.8.

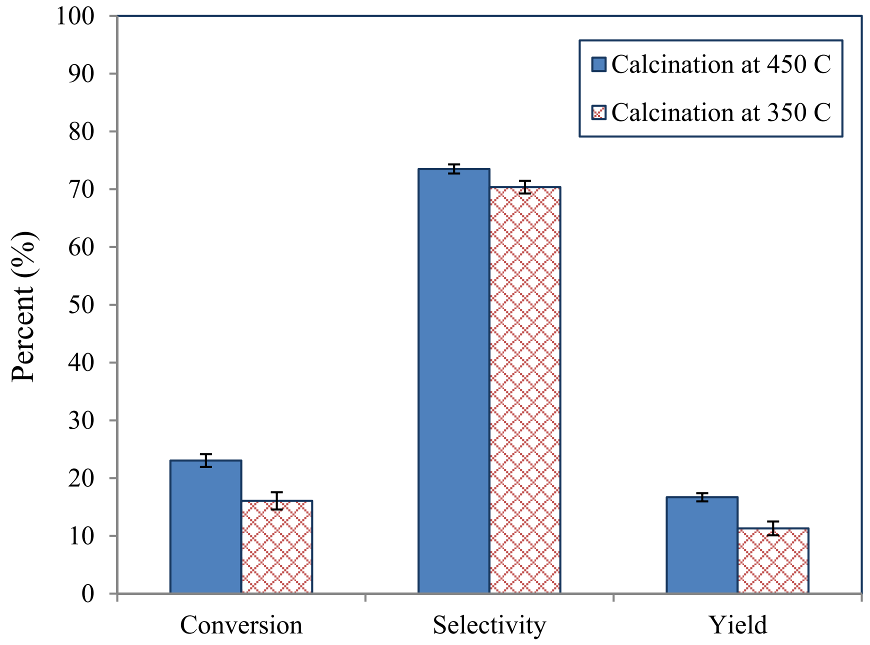

Figure 3.8: Effects of calcination temperature on the activity of HT-C-R catalyst in glucose isomerization at 110 °C (Initial glucose concentration of 100 mg/ml, Feeding flow rate of 0.5 ml/min)

Slightly higher activity for the HT-C-R catalyst in terms of glucose conversion and fructose selectivity and yield was observed for the higher calcination temperature of 450 °C. This could be attributed to the change in basicity of hydrotalcite as a result of the activation at higher temperature. Hydrotalcites are reported to have the maximum basicity when calcined at temperatures between 400 and 600 °C and the increase in basicity could be expected to correlate with an improvement in the catalyst activity.[11]

3.3.2.4 Stability of the Catalysts with Time

In order to study the stability of the catalysts over time, the activity of MgO and HT-C-R catalysts at 120 °C was monitored for 4 hours continuously on stream and the results are shown in Figure 3.9.

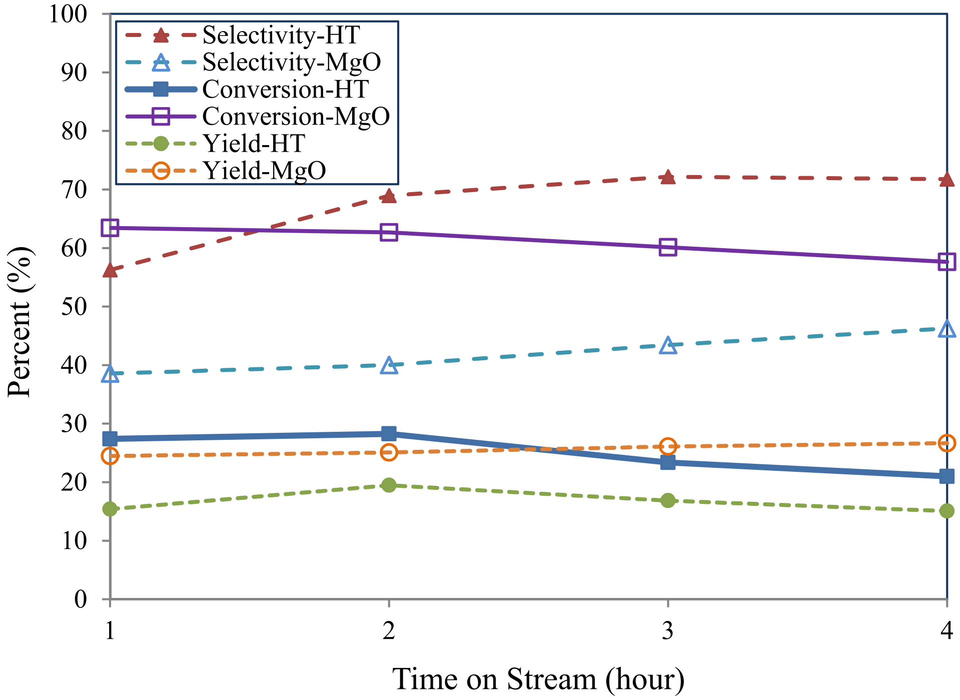

Figure 3.9: Effects of continuous time on stream on HT-C-R (closed symbols) and MgO (open symbols) activities at 120 °C (Initial glucose concentration of 100 mg/ml, Feeding flow rate of 0.5 ml/min)

Little drop in conversion was observed for both catalysts and fructose yield remained almost constant while selectivity was enhanced over time. These results show that HT-C-R and MgO are effective catalysts for glucose isomerization reaction in the continuous-flow reactor with good stability over time. The slight decrease in conversion could be attributed to the accumulation of insoluble humins as the main by-products on the surface of the catalyst particles, which consequently resulted in deactivation of the catalysts.

3.3.3 Characterization of Used Catalysts

In order to study the catalyst deactivation mechanism, used HT-C-R and MgO in the experiments at 120 °C after 4 hours of continuous time on stream were collected and analyzed by TGA in air and their behaviors were compared with the TGA graph of the fresh catalysts. Figure 3.10 shows the TGA and DTG graphs for fresh and used MgO and HT-C-R catalysts.

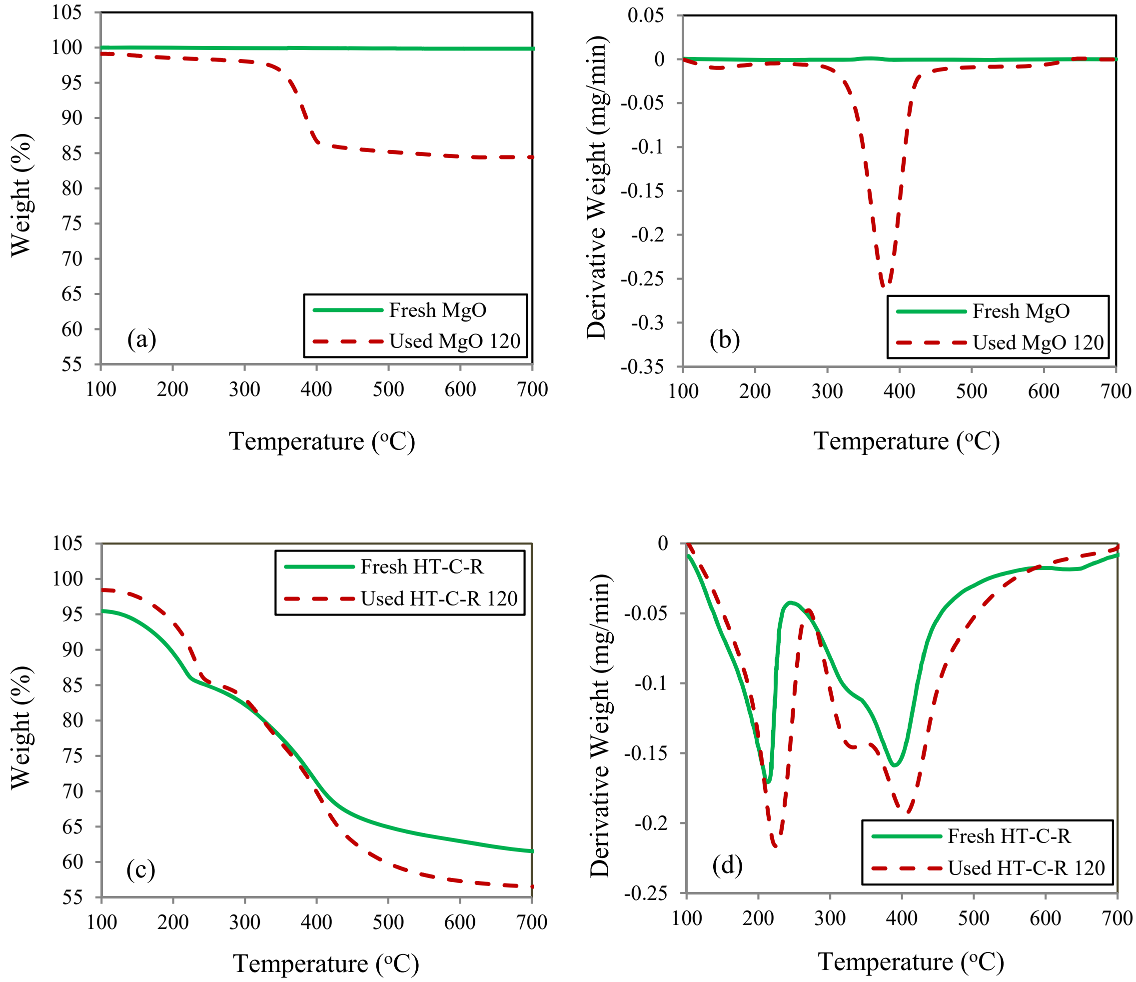

Figure 3.10: TGA and DTG graphs for the used MgO (a and b) and used HT-C-R (c and d) after experiment at 120 °C in comparison with the fresh catalysts

Figure 3.10 a and b shows that, for MgO, the deposition of the insoluble humins on the surface of the catalyst was obvious. There was a weight loss of 15.5% compared to no weight loss for the fresh catalyst. Deposited humins were burned in the air between 300 to 400 ºC and resulted in a sharp peak in DTG curve at 380 ºC. According to Figure 3.10 c and d, the used HT-C-R catalyst showed the same two stages of weight loss as the fresh catalyst. It suggests that this catalyst retains its double layered structure after being used in continuous isomerization experiments at 120 ºC for 4 hours. The used HT-C-R catalyst showed 43.5% weight loss compared to 38.5% for fresh catalyst. The increased weight loss (5%) is resulted from the insoluble humins deposition on the surface of the catalyst. Comparing the difference between the weight losses of the used and fresh MgO (15.5%) with that of the used and fresh HT-C-R (5%) shows that in the presence of MgO more insoluble humins (as the main by-product) were produced compared to HT-C-R in the same operating conditions. This result is in agreement with lower selectivity of MgO compared to HT-C-R in glucose isomerization reaction, which was already discussed. Two peaks at 220 ºC and 400 ºC were observed in the DTG curves for used HT-C-R (Figure 3.10 d). This catalyst did not show a distinct peak for humins decomposition between 300 and 400 ºC as it is coincident with the second weight loss peak of the hydrotalcite structure.

3.4 Conclusions

The present work compares the performances of calcined and rehydrated hydrotalcite, magnesium oxide, Amberlyst A21, PURAL MG30 and PURAL MG30/K_2CO_3 commercial hydrotalcites for isomerization of glucose into fructose in a continuous-flow tubular reactor. The catalysts were characterized using XRD, BET, TGA and FT-IR analyses and the effects of some operating conditions on the performances of the most active catalysts were studied. Based on the results, some key conclusions are summarized as follows:

- Characterization of the the solid base catalysts by XRD, TGA and FT-IR confirmed the hydrotalcite structure for the HT-C-R, HT MG30 and HT MG30/K_2CO_3 catalysts. However, according to XRD data, HT-C-R had more uniform and bigger crystals. The two commercial hydrotalcite catalysts exhibited much larger BET surface areas compared to HT-C-R. MgO was found to have the smallest BET surface area among all other catalysts tested suggesting a nonporous structure. Amberlyst A21 had the most diverse functional groups compared to other catalysts based on FT-IR analyses.

- MgO was the most active catalyst for glucose isomerization reaction with the glucose conversion of 62.7% and the fructose yield of 25.1% at 120 ºC. However, the highest fructose selectivity (78.1%) was obtained by HT-C-R at 100 ºC. This catalyst had the highest fructose yield of 19.5% at 120 ºC after MgO. Despite the large BET surface area of the commercial hydrotalcite catalysts, they did not show a superior activity in glucose isomerization reaction, suggesting that the BET surface area could not be considered as a key indicator of the catalyst activity for this reaction.

- Increasing the reaction temperature from 80 ºC to 120 ºC led to increased glucose conversion and fructose yield in the presence of MgO and HT-C-R catalysts. However, the selectivity of these catalysts decreased with increasing temperature, and the drop in selectivity was greater for MgO compared to HT-C-R.

- Stability test for MgO and HT-C-R over 4 hours of continuous time on stream showed a little drop in glucose conversion and almost constant fructose yield suggesting that these catalysts are effective for glucose isomerization reaction in a continuous-flow reactor with a good stability

- Calcination temperature of 450 ºC was found to be more effective than 350 ºC to improve the catalytic activity and performance of hydrotalcite catalyst for glucose isomerization reaction.

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Chapter 4

4 Catalytic Isomerization of Glucose to Fructose using Activated Hydrotalcite Catalyst in a Continuous-Flow Tubular Reactor: Effects of Reaction Conditions

Abstract

Isomerization of glucose to fructose was studied over calcined and rehydrated hydrotalcite catalyst in a continuous-flow tubular reactor. The characterization and structure of the synthetic (HT), calcined (HT-C) and calcined-rehydrated hydrotalcite (HT-C-R) was studied by thermogravimetric analysis (TGA), X-ray diffraction (XRD), Brunauer-Emmett-Teller (BET) surface area and pore size distribution (PSD) and Fourier transform infrared spectrometry (FT-IR) analyses. The effects of different operating conditions such as reaction temperature and retention time (in terms of both catalyst loading and feeding flow rate) on the isomerization reaction were investigated. It was shown that both catalyst loading and feeding flow rate play important roles in determining the catalytic performance in this isomerization reaction. Glucose conversion and fructose selectivity were found to be more strongly dependent on retention time rather than temperature. Shorter retention time (corresponding to less catalyst loading and higher feeding flow rate) decreases the glucose conversion but improves the fructose selectivity, while higher temperature has detrimental effects on selectivity and increases the glucose conversion. The fructose yield was mostly dependent on feeding flow rate and found to be at its maximum point of 18% at the lowest flow rate of 0.5 ml/min. The results from regenerated hydrotalcite catalyst showed that the activity of the used catalyst can be restored through calcinations-rehydration process and it has a good potential for recycling and reusability.

Keywords: Glucose, Isomerization, Fructose, Continuous-flow tubular reactor, Hydrotalcite, Catalyst characterization, Structural memory effects, Catalyst recycling, Catalyst regeneration

4.1 Introduction

Biomass is considered as a sustainable alternative to fossil fuels and chemicals due to its abundance and eco-friendly nature.[1,2] Effective conversion of biomass into value-added products has attracted much attention and been considered to be one of the key approaches to the production of renewable energy and materials. Glucose, the monomer unit of the natural and abundantly present polysaccharide cellulose, is one of the main building blocks of biomass and is an important substrate for the production of a wide variety of chemicals and biofuels.[3] The conversion of glucose into fructose as an intermediate step for the production of valuable furan derivatives and platform chemicals is of great importance.[4,5] Fructose plays a critical role in the production of 5-HMF (5-hydroxymethyl furfural), which can be subsequently converted to FDCA (2,5-furandecarboxylic acid), a replacement for terephthalic acid in the production of polyesters, and DMF (2,5-dimethylfuran), a biofuel with an energy density higher than that of ethanol.[6] It is also the sweetest of the natural sugars and it is widely used in food industry as sweetener in the form of high fructose corn syrup (HFCS).[7]

Currently, the isomerization of glucose into fructose is carried out on an industrial scale by immobilized enzymes for bulk production of HFCS. However, this process has major drawbacks such as the need for high amounts of expensive enzyme, limited operating temperature range due to the sensitivity of enzymes to process parameters and the possibility of microbial growth in the system.[3,4,8] Chemical catalysts have been used as alternatives to enzymes in the isomerization process and reported to make the process more rapid and robust than the biochemical process. Moreover, the chemical catalysts have wider operating temperature range, longer lifetime and higher resistance to impurities.[1] The glucose isomerization into fructose is an equilibrium controlled reaction and the maximum attainable degree of glucose conversion is governed by the thermodynamic equilibrium between both sugars (glucose and fructose) at the reaction temperature.[9,10] Commercial enzymes result in equilibrium glucose conversions of 45-58% depending on temperature.[11] As shown in Figure 4.1, the isomerization of glucose to fructose is accompanied by production of a variety of by-products. Thus a highly selective, efficient and inexpensive catalyst is essential to control the undesirable reactions and to improve the reaction kinetics.

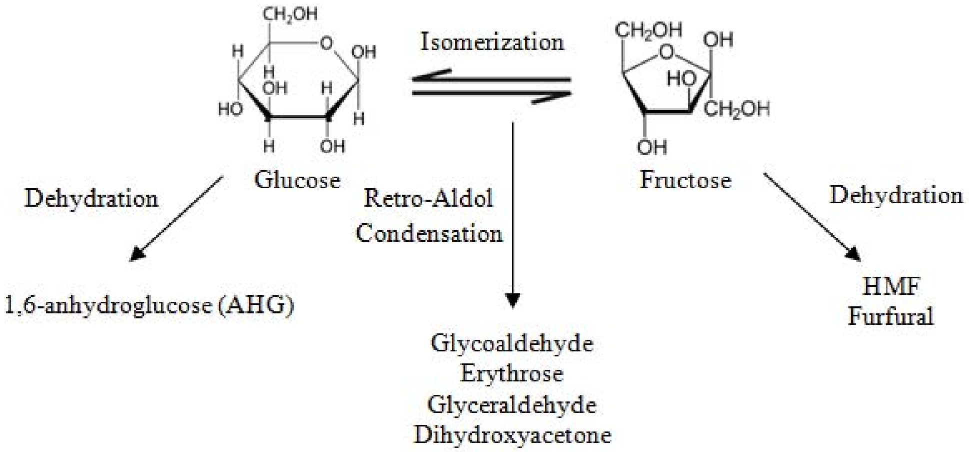

Figure 4.1: Reaction pathway for isomerization of glucose to fructose and by-products [12]

Different kinds of homogeneous and heterogeneous acid and base catalysts have been applied to the isomerization process of glucose to fructose. It has been reported that at low temperatures, the glucose isomerization reaction could be catalyzed by base catalysts.[3,12] In addition, heterogeneous or solid catalysts have several advantages compared to homogenous ones, including lower impact on the systems and global environment and reusability.[2] They will also facilitate large-scale industrial operations. Therefore, great efforts have been made to identify the potential solid catalysts for the glucose to fructose isomerization reaction.

Hydrotalcites are double layered hydroxides composed of MgO and $MgAl_2O_4$ and have been widely used as heterogeneous solid catalysts for base-catalyzed reactions.[1,13] Calcination of hydrotalcites between 300-500 °C removes the interlayer water, anions and hydroxyls, effectively destroys the hydrotalcite double layered structure and results in an atomic mixture of metal (Mg and Al) oxides. The calcined hydrotalcite can return to its initial structure when it is exposed to water or water vapor (rehydration).[1,14,15] This property is known as "structural memory effects" and has many catalytic applications.[14] The base property of the hydrotalcite depends on its changed structure by a calcination and rehydration processes and it has been reported that the rehydration process increases the exposed weak base sites of hydrotalcite catalyst which is favorable for glucose isomerization.[1]

Using hydrotalcites as solid base catalysts in isomerization of glucose to fructose has been reported by some researchers. Moreau et al. compared the effects of cation-exchanged A, X, Y zeolites and calcined hydrotalcites (Mg/Al=2.5 and 3) at 450 °C for the isomerization of glucose to fructose at 95 °C, 250 g/l of initial glucose concentration, and up to 20 wt% of catalyst. Hydrotalcites were found to be less selective with up to 66% fructose selectivity and up to 42% glucose conversion compared to cation-exchange zeolites. However, no leaching effect was observed for hydrotalcites despite of relatively significant leaching problem for other catalysts tested. It was concluded that the relatively lower selectivity of hydrotalcite catalysts compared to zeolites was due to their relatively stronger basic properties.[16]

Yu et al. studied the isomerization of glucose to fructose over three types of synthesized Mg-Al hydrotalcites with the ratio of Mg/Al=3: as-synthesized hydrotalcite, calcined hydrotalcite and rehydrated hydrotalcite. The catalytic reactions were performed at 100 °C for 5 hours. Among the catalysts tested, the highest glucose conversion of 76% was obtained by calcined hydrotalcite catalyst, while it showed the lowest fructose selectivity of 31%. This was believed to be the result of strong and abundant base sites of calcined hydrotalcite due to the formation of Mg-Al mixed oxide with high surface area that leads to conversion of a considerable amount of glucose into degradation products. Rehydrated hydrotalcite showed the highest fructose yield of 30% compared to calcined hydrotalcite and as-synthesized hydrotalcite. Thus, it was reported that the rehydration process could be an effective method for increasing catalytic performance of hydrotalcites in the glucose isomerization process. The authors also investigated the effects of reaction temperature and time and concluded that they served as crucial factors on the catalytic performance of hydrotalcite. Temperature of 80 °C and reaction time of 3 hours were found to be the appropriate reaction conditions to obtain the highest fructose yield of around 35%.[1]

In another work by Lecomte et al. isomerization of glucose to fructose was performed at 90 °C in the presence of a commercial hydrotalcite catalyst in its carbonate, hydroxide and mixed carbonate-hydroxide forms. The hydrotalcite catalyst in its hydroxide form was found to be more selective and active than the carbonate form. However, the high selectivity (>90%) of fructose dropped rapidly after 15% of glucose conversion for all of the catalyst forms. It was reported that the rehydration of the catalyst after calcination strongly increases the activity of the catalyst by the factor of 10, while the fructose selectivity remains almost constant. Temperature and initial glucose concentration were found to have great effects on initial reaction rate but no significant impact on selectivity.[15]

Most of these studies in the field of glucose isomerization were performed in batch mode and little attention has been paid to use continuous-flow reactor, which is more desirable for application at large scale for industrial and commercial production. Therefore, the objective of the present study is to investigate the isomerization of glucose into fructose in a continuous-flow tubular reactor designed and constructed in-house by the authors in the presence of activated hydrotalcite catalyst. The effects of different reaction conditions in continuous mode such as temperature, flow rate and catalyst loading defined as weight hourly space velocity (WHSV) on the conversion, selectivity and yield of the reaction were studied. A stability test was also performed to investigate the possibility of reusing the hydrotalcite catalyst. Comprehensive characterization of the catalyst including thermal stability tests (TGA), surface area, average pore diameter and total pore volume (BET), identification of functional groups (FT-IR) and crystalline structure (XRD) were also performed and compared for the synthetic, calcined and calcined-rehydrated hydrotalcites.

4.2 Materials and Methods

4.2.1 Materials

D-(+)-glucose (>99.5%) and synthetic hydrotalcite (i.e., magnesium aluminum hydroxyl carbonate, $Mg_6Al_2(CO_3)(OH)_{16}.4H_2O$, Mg/Al molar ratio of 3:1) were purchased from

Sigma-Aldrich. HPLC grade water for preparing the mobile phase for HPLC analysis was obtained from EMD Millipore Milli-Q water system with resistivity of 18.2 MΩ.cm.

4.2.2 Catalyst Preparation

Synthetic hydrotalcite (HT) activation/pelletization process was performed as follows: HT was first calcined at 450 °C in a muffle furnace with the heating rate of 10 °C/min for 10 hours (HT-C) and then rehydrated by adding deionized water after cooling inside a desiccator to form a soft paste. The paste was dried overnight in an oven at 80 °C and then crushed by a mortar and pestle. After sieving, particles between 300-840 μm (Mesh No. 50 to Mesh No. 20) were collected for using as activated solid catalyst particles in the experiments (HT-C-R).

4.2.3 Continuous-Flow Reactor Setup and Experimental Procedure

The catalytic isomerization of glucose to fructose was performed in presence of activated hydrotalcite (HT-C-R) as the heterogeneous solid base catalyst in a continuous-flow tubular reactor designed and constructed in-house by the authors. The schematic diagram and detailed description of this lab-scale tubular reactor setup as well as the experimental procedure have been presented in our previous work (Chapter 3).

The experiments were performed at two different temperature levels: Low temperature experiments at 90, 100 and 110 °C using 4 g of catalyst and high temperature experiments at 120, 130 and 140 °C using 2 g of catalyst. In all of the experiments the effects of different feeding flow rates of 0.5, 1.0 and 1.5 ml/min were examined. The experiments at 120 and 140 °C were also carried out without catalyst as blank tests and at flow rate of 0.5 ml/min to investigate the performance of catalyst in the glucose isomerization reactions. For all of the experiments, initial glucose concentration was 50 mg/ml, pressure of the reactor was 10 bars and the time on stream was 4 hours and no detectable soluble by-product or any other intermediate was found in HPLC chromatographs.

4.2.4 Product Analyses

The product samples collected from the experiments were analyzed using an HPLC system to determine the amount of product (fructose) produced and the amount of feedstock (glucose) consumed and the results for all of the experiments were calculated and reported based on conversion, selectivity and yield. The detailed description of the HPLC system and analysis procedure as well as the definitions of conversion, selectivity and yield have been presented in our previous work (Chapter 3).

4.2.5 Catalyst Characterization Methods

Synthetic hydrotalcite (HT), calcined hydrotalcite (HT-C) and calcined-rehydrated hydrotalcite (HT-C-R) catalyst samples were comprehensively characterized through various analyses including TGA, FT-IR, BET/PSD and XRD. The detailed description of the analyzers as well as analyses procedures have been presented in our previous work (Chapter 3).

4.3 Results and Discussion

4.3.1 Characterization of Fresh Catalysts

XRD patterns of fresh HT, HT-C and HT-C-R catalyst samples are shown in Figure 4.2. The patterns clearly show that the HT has a layered structure which is well consistent with those reported in literature.[1,14,17] The peaks observed at $2\theta=11.6^{\circ}$, 23.3°, 34.7°, 60.6°, 62.1° corresponding to the basal (003), (006) and (009) planes and nonbasal (110) and (113) planes, respectively, are the characteristic XRD peaks for HT catalyst and show its double layered hydroxide structure.[1,18]

However, no peaks corresponding to layered structure of hydrotalcite were observed in XRD for HT-C catalyst which indicates that the layered structure was destroyed completely by the calcinations process at 450 °C and resulted in the crystalline structure of Mg-Al mixed oxides. The XRD pattern for the HT-C-R shows that the layered structure was restored during the rehydration process. This was attributed to and confirmed the "structural memory effects" of hydrotalcite.[1,14]

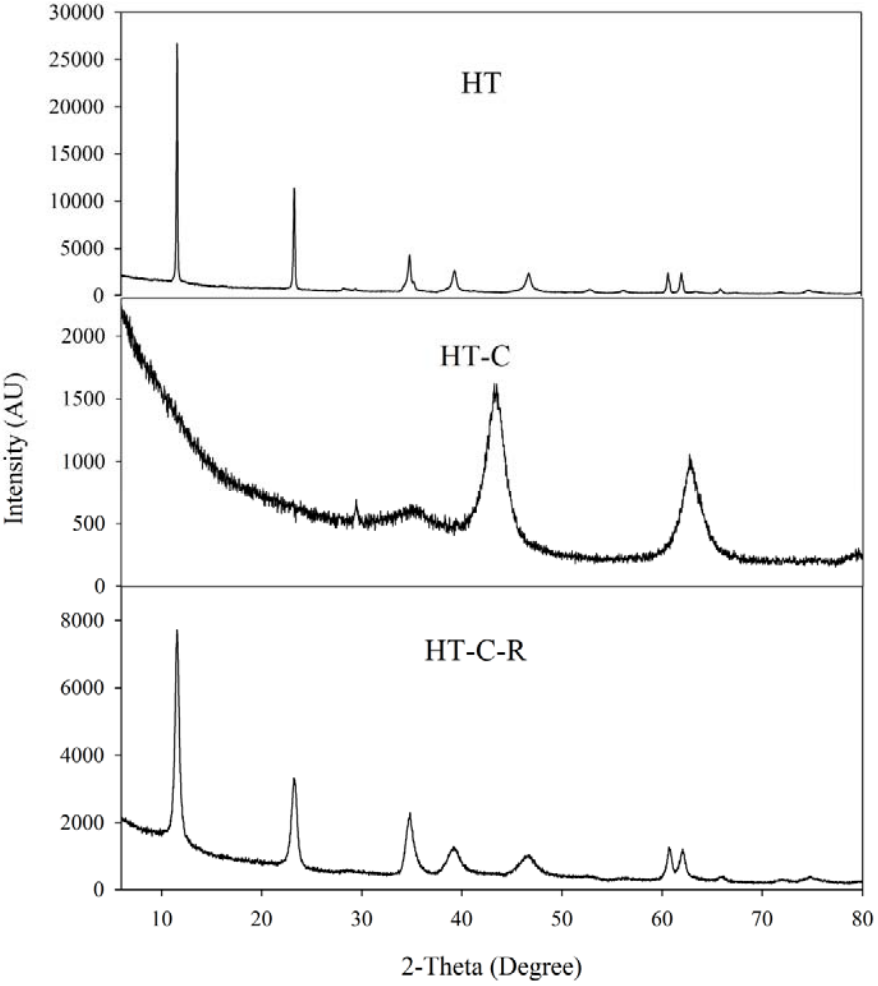

Figure 4.2: XRD patterns of the fresh HT, HT-C and HT-C-R

TGA graphs for HT, HT-C and HT-C-R catalyst samples are shown in Figure 4.3. According to the TGA graphs, the total weight loss for HT-C (7.6%) was not significant compared to HT (44.7%) and HT-C-R (38.5%). HT and HT-C-R both showed two stages of weight loss which was accompanied by endothermal transformation.[17] The first weight loss occurred between 100 and 250 ºC and corresponded to the loss of interlayer water molecules and the second weight loss took place after 250 ºC which was attributed to the removal of condensed water molecules and loss of carbonate anions via the formation of carbon dioxide from the brucite layer.[17,19,20] But calcined hydrotalcite did not show the two-step thermal decomposition as calcination at 450 ºC had already destroyed the layered structure of HT and resulted in the formation of Mg-Al mixed oxide. However, after rehydration the layered structure of hydrotalcite was recovered as shown in Figure 4.3 a. Derivative thermogravimetric (DTG) data (i.e. the first and second weight losses and temperatures for HT and HT-C-R) are reported in Table 4.1. According to DTG curves (Figure 4.3 b) the first weight loss region showed a peak at 237 and 213 °C for HT and HT-C-R, respectively. The second weight loss region for synthetic hydrotalcite exhibited two endothermic peaks occurring at 329 and 431 °C. This may be attributed to the simultaneous loss of water and carbon dioxide.[17] However, for the rehydrated HT only one major peak at 390 °C accompanied by a weak shoulder at around 320 °C was observed indicating that after rehydration of calcined HT using decarbonated/deionized water, the carbonate anions were significantly substituted by water molecules in the double layered structure of hydrotalcite and no isolated peak for CO_2 loss was observed.

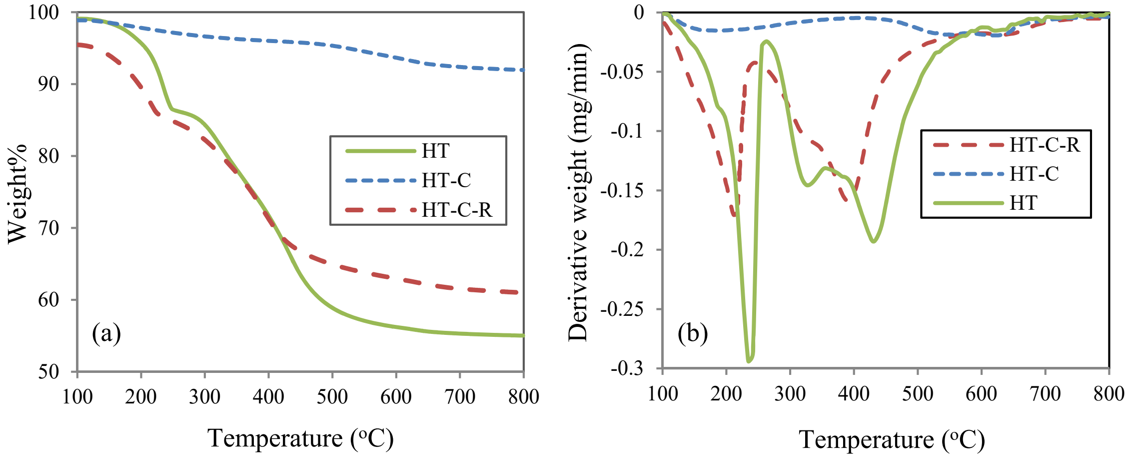

Figure 4.3: TGA (a) and (b) DTG (b) graphs for the fresh HT, HT-C and HT-C-R

Table 4.1: TGA weight loss results for the fresh HT and HT-C-R

Catalyst	Temperature (°C)	First Weight Loss (%)	Temperature (°C)	Second Weight Loss (%)
HT	237.2	13.54	329.3, 431.8	31.14
HT-C-R	213.6	15.15	390.3	23.30

The results of N_2 physisorption analysis are summarized in Table 4.2. Calcination of HT resulted in a large increase in BET surface area from 7 to 211 m^2/g. As previously mentioned, when HT is calcined the layered structure is completely destroyed and Mg-Al mixed oxide is formed which results in a significant increase in exposed surface area. The increased BET surface area could also be attributed to the formation of micropores and mesopores as a result of calcination which can also be observed in great increase of total pore volume.[20] After the rehydration process and restoration of the initial layered structure of hydrotalcite, the BET surface area decreased, however it was higher than the initial surface area of HT which was attributed to the exfoliation and vertical breakage of the layers during the rehydration process.[1] The increase in average pore diameter after rehydration compared with the HT may also be explained by the breakage of the layers.

Table 4.2: Textural properties of the fresh HT, HT-C and HT-C-R

Catalyst	BET Surface Area (m^2/g)	Average Pore Diameter (nm)	Total Pore Volume (cm^3/g)
HT	7	8	0.02
HT-C	211	2	0.12
HT-C-R	19	19	0.09

FT-IR spectra of the HT and HT-C-R (Figure 4.4) show a broad absorption at around 3400 cm^{-1} which is attributed to the O-H stretching vibration of the interlayer water molecules and hydroxyl groups in hydroxide layer of the catalyst. The small shoulders between 2840 and 2940 cm^{-1} are due to the hydrogen bonding between water and carbonate ions in the interlayer and almost disappeared in the FT-IR spectrum of HT-C-R indicating the substitution of carbonate ions with water molecules in rehydrated HT. The weak absorption at 1610 cm^{-1} is ascribed to the bending vibration of water molecules in the interlayer. The strong and sharp peak at 1370 cm^{-1} indicates the stretching vibration of carbonate anions. According to Figure 4.4 the intensity of this peak is significantly reduced after rehydration which again shows the loss of carbonate anions during rehydration process. The shoulders between 570 and 800 cm^{-1} may be due to the stretching and bending vibrations of Al-O or Mg-Al-O bonds in the brucite layer. Almost all of the peaks vanished after calcinations at 450 ºC (HT-C) which was again attributed to the complete thermal decomposition of hydrotalcite double layered structure and formation of mixed metal oxides. This was also confirmed by the XRD, TGA and BET results. The FI-IR results are in good agreement with previous data reported in literature.[18,21]

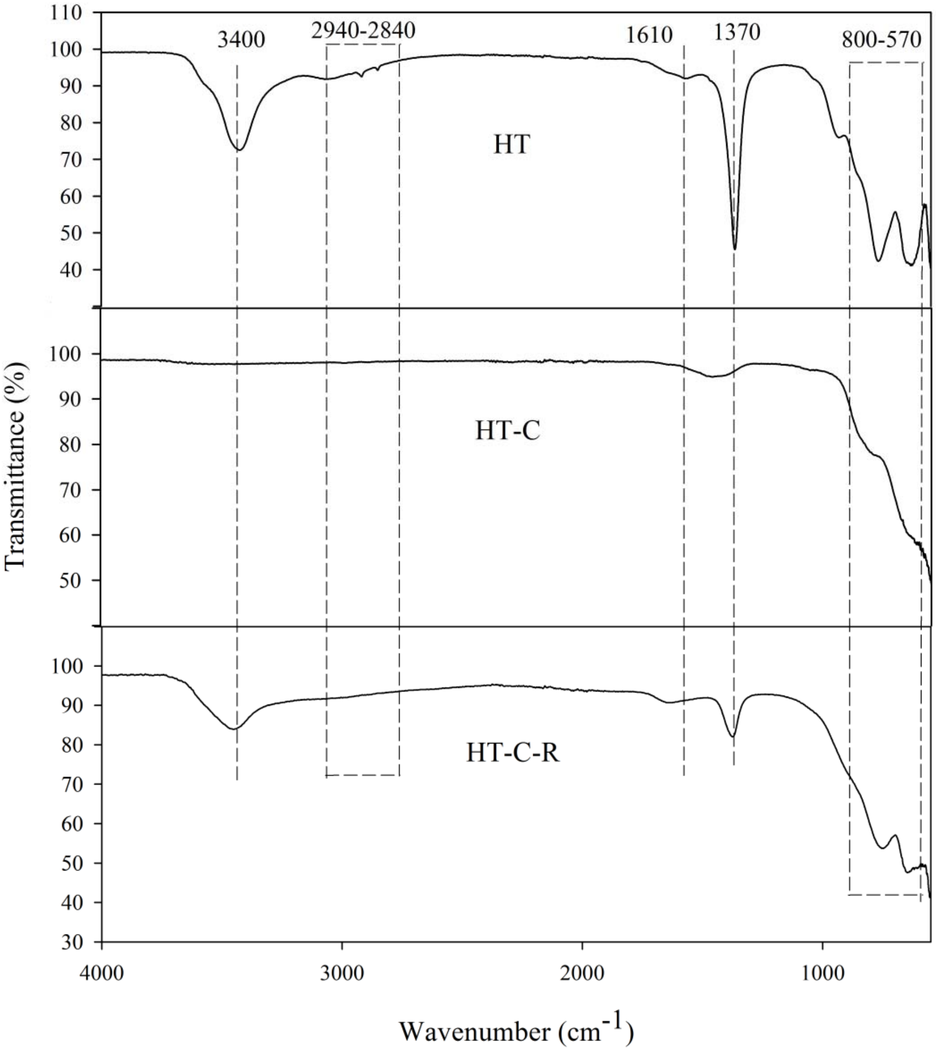

Figure 4.4: FT-IR spectra of the fresh HT, HT-C and HT-C-R

4.3.2 Catalytic Isomerization of Glucose to Fructose

4.3.2.1 Catalytic Performance of Activated Hydrotalcite in Glucose Isomerisation

The results of glucose conversion, fructose selectivity and yield for the reactions at 120 and 140 °C with and without activated HT catalyst are reported in Table 4.3. In the presence of catalyst, glucose conversion was significantly enhanced and the fructose yield was remarkably high (17-18%) compared to the blank tests. It should be noted that a fructose yield of 17-18% is equivalent to more than 40% of the thermodynamic yield achieved with enzymes after long reaction times as glucose isomerization into fructose is an equilibrium controlled reaction and maximum attainable degree of glucose conversion is governed by the thermodynamic equilibrium.[9,10]. Therefore, the results confirmed that activated HT promoted the isomerization of glucose into fructose.

Table 4.3: Performance of activated HT catalyst in isomerization of glucose to fructose in comparison with the blank tests [a]

Reaction Conditions		Conversion (%)	Selectivity (%)	Yield (%)
T=120 °C	Without HT	1.6	16.9	0.3
	With HT [b]	31.5 ± 3.1	56.0 ± 1.2	17.6 ± 1.0
T=140 °C	Without HT	2.2	29.2	0.6
	With HT [b]	62.2 ± 2.2	29.1 ± 1.7	18.1 ± 0.4

[a] Initial glucose concentration of 50 mg/ml, Feeding flow rate of 0.5 ml/min
[b] Catalyst loading of 2 g (WHSV=0.75 hr^{-1})

To investigate the effects of diffusion and internal mass transfer limitations, two other experiments were also performed using larger catalyst particles size (840-1200 μm, Mesh No. 20 to Mesh No. 16) and smaller catalyst particles size (100-300 μm, Mesh No. 140 to Mesh No. 50) at the same operating condition as the experiment with catalyst particles size 300-840 μm (Mesh No. 50 to Mesh No. 20) at 120 °C. The results did not show any significant difference in conversion, selectivity and yield suggesting that diffusion and internal mass transfer are not limiting factors in our experiments.

Figures 4.5 a-f show the effects of different operating conditions including temperature, flow rate and catalyst loading on the isomerization reaction in the presence of HT-C-R (activated hydrotalcite). Glucose conversion and fructose selectivity appear to be in inverse proportion: The maximum glucose conversion of 63.1% was achieved with low fructose selectivity of 21.9% and the highest fructose selectivity of 74.7% was accompanied by a low glucose conversion of 13.5%. This could be attributed to the degradation of the fructose into glyceraldehydes and dihydroxyacetone via retro-adol condensation with increasing fructose concentration in the reaction media. The maximum fructose yield (18.7%) was obtained with medium fructose selectivity of 38.3% and glucose conversion of 48.8% at the reaction temperature of 130 ^{o}C and feeding flow rate of 0.5 ml/min with 2 g catalyst loading (WHSV=0.75 hr^{-1}), while the highest fructose selectivity (74.7%) was achieved at the reaction temperature of 120 ^{o}C and feeding flow rate of 1.5 ml/min with 2 g catalyst loading (WHSV=2.25 hr^{-1}).

4.3.2.2 Effects of Reaction Temperature

According to Figure 4.5, at both low and high temperature ranges, increasing the temperature led to higher glucose conversion (kinetics effect) and lower fructose selectivity (thermodynamics effect). This result was in agreement with previous findings on the effects of temperature on glucose isomerization with hydrotalcite catalyst.[1,22] Thus, the fructose yield, which is the product of conversion and selectivity remained somewhat constant.

The decrease in selectivity with temperature indicates that the isomerization reaction was accompanied by some side reactions, which dominate in higher reaction temperature and result in the formation of undesirable products. The most important by-products of this reaction were insoluble humins as a product of self-polymerization and condensation of glucose and fructose, which were visually detectable as brownish depositions on the surface of the catalyst particles after completion of the reaction. The caramelization reaction was also one possible pathway of by-product formation. Caramelization is the oxidation of sugars and is usually favorable at temperatures higher than 120 ^{o}C and results in appearance of brown color in the samples.[23] The amber color observed in the product samples of high temperature range reaction in this work might be an evidence for this chemical reaction.

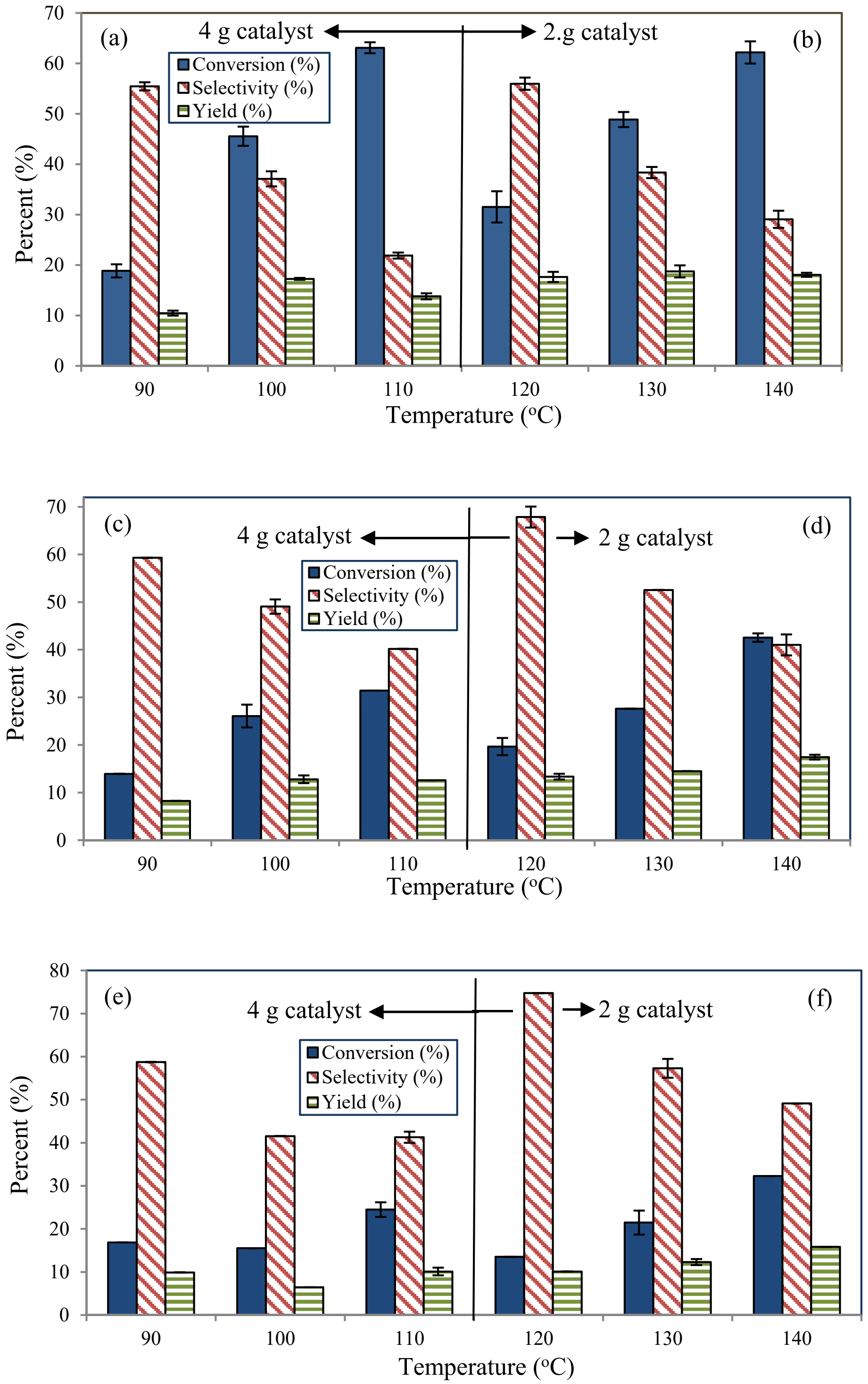

Figure 4.5: Effects of temperature and catalyst loading on conversion, selectivity and yield for glucose isomerization reaction in the presence of activated HT at feeding flow rate of 0.5 ml/min (a, b), 1.0 ml/min (c, d), 1.5 ml/min (e, f) (Initial glucose concentration of 50 mg/ml)

4.3.2.3 Effects of Retention Time

The effects of retention time (WHSV) on glucose isomerization reactions was studied in terms of the effects of catalyst loading at a fixed feeding flow rate and the effects of feeding flow rate at a fixed catalyst loading.

Effects of Catalyst Loading

Comparing the bar graphs at110 ºC and120 ºC in Figures 4.5 a and b (0.5 ml/min feeding flow rate) shows that decreasing the amount of catalyst loading by half (from 4 g to 2 g), corresponding to doubling the WHSV and reducing the retention time to half, had a negative effect on glucose conversion and a positive effect on fructose selectivity.

According to the results explained in the previous section, glucose conversion increases with increasing the temperature. However, at 110 ºC and feeding flow rate of 0.5 ml/min (Figures 4.5 a and b) a further increase in the reaction temperature accompanied by decreasing the catalyst loading from 4 g (WHSV=0.375 h^{-1}) to 2 g (WHSV=0.750 h^{-1}) resulted in conversion drop from 63.1 to 31.5%. If the catalyst loading at 120 ºC was the same as that of 110 ºC (i.e., 4 g or WHSV=0.375 h^{-1}), it was expected that the conversion would further increase. However, the lower catalyst loading resulted in 50% drop in glucose conversion. This drop was attributed to the shorter retention time (contact time between feedstock and catalyst) as a result of the lower availability of catalyst inside the reactor. Thus, it can be concluded that glucose conversion depends more on catalyst loading (retention time) than reaction temperature. Increasing trend in glucose conversion with temperature was observed again when catalyst loading was fixed at 2 g and temperature was increased from 120 to 130 and 140 ºC. The same trend for glucose conversion was observed for the other tested flow rates when one compares Figure 4.5 c with d (1.0 ml/min feeding flow rate), and Figure 4.5 e with f (1.5 ml/min feeding flow rate).

Again, according to the results explained in the previous section, fructose selectivity decreases with increasing temperature. However, at 110 ºC and feeding flow rate of 0.5 ml/min (Figures 4.5 a and b) further increase in the reaction temperature accompanied by a decrease in the catalyst loading from 4 g (WHSV=0.375 h^{-1}) to 2 g (WHSV=0.750 h^{-1})

resulted in a significant increase in selectivity from 21.9 to 56.0%. Since the lower catalyst loading is equivalent to higher WHSV and shorter retention time, this result showed that longer retention time (higher catalyst loading) and higher reaction temperature have detrimental effects on fructose selectivity, and the formation of by-products increases with the reaction time. The same trend was observed for the other tested flow rates when one compared Figure 4.5 c with d (1.0 ml/min feeding flow rate) and Figure 4.5 e with f (1.5 ml/min feeding flow rate). In almost all of the experiments, higher fructose selectivity was compensated by lower glucose conversion, and consequently, fructose yield did not change notably.

Effects of Feeding Flow Rate

The effects of feeding flow rate on glucose isomerization reaction can be seen by comparing Figures 4.5 a, c, e with b, d, f at identical temperatures and catalyst loadings. For ease of comparison, the effects of feeding flow rate at 120 ºC with initial glucose concentration of 50 mg/ml and 2 g catalyst loading are shown in Figure 4.6. Fructose selectivity increased with increasing feeding flow rate, while glucose conversion decreased with a small drop in fructose yield. This trend was observed for all other temperatures and catalyst loadings. Increasing the flow rate corresponded to shorter retention time (higher WSHV) inside the reactor and shorter retention/reaction time is in favor of higher selectivity. It also led to lower glucose conversions due to shorter contact between the reactant molecules and catalyst surface inside the reaction zone. These results were in agreement with those that were obtained and explained for the effects of retention time by varying the catalyst loading.

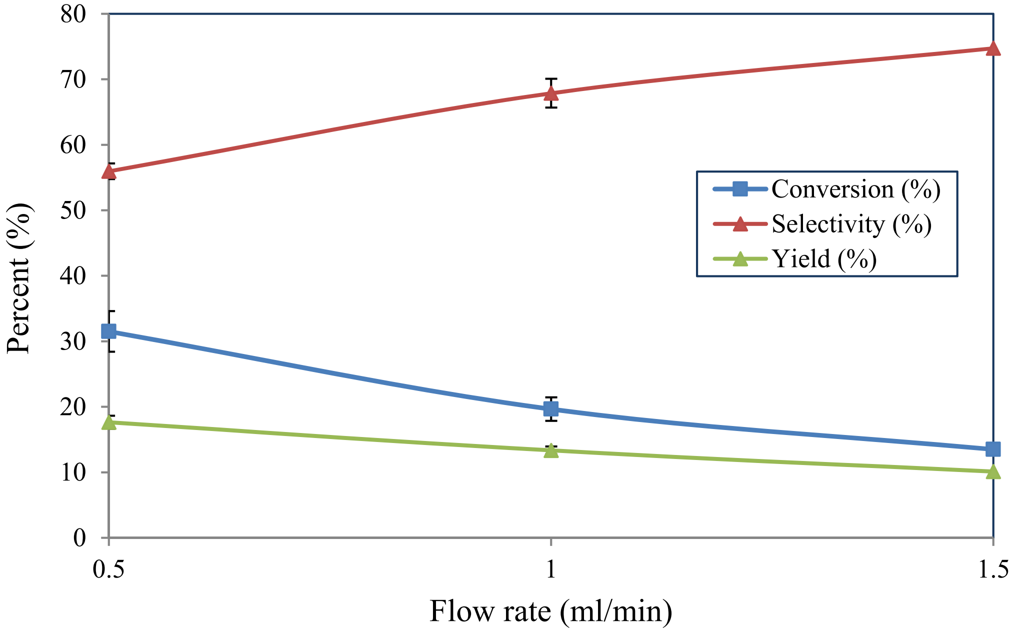

Figure 4.6: Effects of feeding flow rate on glucose isomerization at 120 °C (Initial glucose concentration of 50 mg/ml and 2 g catalyst loading)

4.3.2.4 Catalyst Regeneration and Recycling Study

The feasibility of regenerating and reusing the used hydrotalcite catalyst was studied by conducting the isomerization experiments with the used catalyst without any further treatment and also after calcination and rehydration (reactivation). After completion of the isomerization experiment (8 hours of continuous time on stream) using fresh catalyst at 110 °C with an initial glucose concentration of 50 mg/ml and a feeding flow rate of 0.5 ml/min, the reactor was cooled and the catalyst was washed in-situ by pumping distilled water through the reactor. Then it was left overnight inside the reactor before being used in the recycling experiments. The experiments with used catalyst were performed under the same operating conditions (i.e., temperature, initial feedstock concentration and feeding flow rate). First, the untreated catalyst was reused and then the used catalyst was regenerate through calcination at 450 °C and rehydration and reused. The performances of the used and regenerated catalysts are compared with the fresh catalyst in Table 4.4.

Table 4.4: Comparison of the fresh, used and rgenerated HT-C-R activity in glucose isomerization reaction at 110 °C

Catalyst	Conversion (%)	Selectivity (%)	Yield (%)
Fresh HT-C-R	63.1 ± 1.1	21.9 ± 0.6	13.8 ± 0.6
Untreated Used HT-C-R	30.2	39.2	11.8
Regenerated Used HT-C-R	59.3	22.8	13.5

[a] Initial glucose concentration of 50 mg/ml, Feeding flow rate of 0.5 ml/min and 4 g catalyst loading (WHSV=0.375 hr^{-1})

The untreated used catalyst showed lower glucose conversion and higher fructose selectivity compared to the fresh catalyst without noticeable loss in fructose yield. The same trend for glucose conversion and fructose selectivity was reported by others after reusing zirconosilicate as a solid catalyst at 100 °C for 60 min in a batch reactor.[24] They reported a decrease in fructose yield from 26% to 19% after the first run. However, in our experiment no significant decrease in fructose yield in the continuous-flow reactor was observed. In the case of regenerated used catalyst, the performance of the catalyst was almost the same as the fresh catalyst in terms of conversion, selectivity and yield. It indicates that the activity of the used HT-C-R catalyst could be restored after calcinations-rehydration process and could be an effective catalyst for isomerization of glucose to fructose with a good potential for recycling and reusability.

4.4 Conclusions

Calcined and rehydrated hydrotalcite was used in the isomerization reaction of glucose into fructose in hot compressed water using a continuous-flow tubular reactor. Some key conclusions are summarized as follows:

- Characterization of the hydrotalcite catalysts confirmed the double layered structure and the memory effects of hydrotalcite through the calcination and rehydration process. It was also revealed that after rehydration of calcined hydrotalcite, carbonate anions are significantly substituted by water molecules in the layered structure.

- From all of the results, it appears that hydrotalcite was an effective catalyst for isomerization of glucose to fructose in a continuous-flow reactor with good glucose conversion, fructose selectivity and yield.
- The maximum fructose yield in the presence of activated hydrotalcite catalyst was 18.7% at 130 ºC (48.8% glucose conversion and 38.3% fructose selectivity) with feeding flow rate of 0.5 ml/min and 2 g catalyst loading, which is considerably higher than the uncatalyzed (blank) reaction (0.3-0.6%).
- Higher temperature as well as higher catalyst loading and lower feeding flow rate (longer retention time) were found to be favorable for higher glucose conversion but had detrimental effects on fructose selectivity.
- The untreated used HT-C-R catalyst showed lower glucose conversion and higher fructose selectivity compared to the fresh catalyst without significant loss in fructose yield. However, the regenerated used catalyst exhibited almost the same performance as the fresh catalyst in terms of conversion, selectivity and yield. Suggesting that the activity of the used catalyst can be restored through calcinations-rehydration process.

4.5 References

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Chapter 5

5 Catalytic Dehydration of Fructose to 5-HMF using Heterogeneous Solid Acid Catalysts in a Biphasic Continuous-Flow Tubular Reactor

Abstract

In this work, various solid acid catalysts, i.e., niobium based catalysts, Amberlyst 15 and Amberlyst 36, were comprehensively characterized through various analyses including thermogravimetric analysis (TGA), X-ray diffraction (XRD), temperature programmed desorption of ammonia (TPD-NH_3), Brunauer-Emmett-Teller (BET) surface area and pore size distribution (PSD), Fourier transform infrared spectrometry (FT-IR) and pyridine adsorbed FTIR (Py-FTIR). Their activities for dehydration of fructose to 5-hydroxymethylfurfural (5-HMF) were studied in a biphasic continuous-flow tubular reactor. The effects of different reaction parameters such as initial fructose concentration, reaction temperature, feeding flow rate, addition of a phase transfer catalyst (NaCl), presence or absence of an organic phase, and aqueous to organic phase ratio were studied and the best operating conditions were found to be 150 °C temperature, 0.25 ml/min feeding flow rate, 200 mg/ml NaCl concentration, 200 and 400 mg/ml of fructose concentration and aqueous to organic phase ratio of 1:5 and 1:10. The niobium phosphate, synthetic niobium sulfate and Amberlyst 36 were found to be very active catalysts, leading to 54-59% HMF yield at the optimum operating conditions. Amberlyst 36 exhibited the highest HMF selectivity of 70% at 150 °C, and therefore it was selected as the best catalyst for fructose dehydration reaction. Reusability tests with the used catalyst demonstrated superb stability of the catalyst for a long time-on-stream suggesting that this catalyst has the capability to be recycled and reused without losing much of its activity.

Keywords: Fructose Dehydration, 5-HMF, Biphasic continuous-flow tubular reactor, Niobium phosphate, Amberlyst 36, Catalyst characterization, Catalyst stability, Catalyst reusability

5.1 Introduction

Biofuels and biomaterials are ideal and interesting alternatives due to limited fossil fuels resources.[1,2] Among current biofuel sources, 5-hydroxymethylfurfural (HMF) as a versatile and polyfunctional compound has attracted increasing attention.[3] HMF is an important intermediate and platform chemical that can be converted into liquid transportation fuels and various valuable chemicals such as 2,5-furandicarboxylic acid (FDCA), levulinic acid (LA) and 2,5-dimethylfuran (DMF) through specific catalytic transformations.[4,5] HMF can be generated from hexoses by loss of three molecules of water in acid catalyzed reactions.[6] Although the cheapest hexose is glucose as it is considered as a key component of cellulosic biomass, fructose has proven to be more favorable feedstock than glucose for HMF production with higher yields of HMF.[4] On one hand, glucose has more stable ring structure than fructose, while the formation of HMF from hexoses proceeds through an open chain mechanism. Low fraction of open chain formed in solution when glucose is used as a feedstock would result in low enoliation rates.[4,6] On the other hand, glucose must first isomerize to fructose before its conversion to HMF. As the isomerization process is via alkali-catalyzed reactions, high yields of HMF from glucose in acidic media is not expected.[4]

In the past years, several studies have been published regarding the production of HMF from fructose and glucose in various solvents with different acidic catalysts, either homogeneous or heterogeneous.[7–11] Among the possible reaction media, water is the most interesting one from both economic and environmental point of view. Application of heterogeneous catalysts is also more favorable as the catalysts are recyclable, thus facilitating environmental-friendly and cost-effective conversion. Moreover, heterogeneous catalysts have shown a superior behavior in terms of HMF selectivity.[3] However, most of solid acid catalysts cannot maintain their acidity in water without deactivation of their acid sites and they found to have low HMF yields even at high reaction temperatures and low selectivity due to uncontrolled rehydration of HMF to levulinic and formic acids. [2,5,12] One of the proposed methods to solve this problem is the in-situ extraction of HMF from the aqueous reaction media using an organic extractive solvent, immiscible in water to avoid its successive transformation.[4,12]

Removal of HMF from the aqueous reaction medium using an extractive solvent was first introduced by Cope by using water/methyl isobutyl ketone (MIBK) solvent system in HMF production from glucose.[13] MIBK is a good extracting organic solvent for sugars dehydration in water that could suppress the undesired side reactions and extract more HMF into organic phase.[3] However, the partition coefficient of HMF for MIBK/water solution is close to unity which means that large amounts of MIBK are needed to extract HMF from the aqueous phase.[4] The isolated yield of HMF in the work by Cope was reported to be 21−25% by reacting a 50 wt% aqueous glucose solution at 160 °C for around 9 hours in the presence of 20 volumetric equivalents of MIBK.[13]

Kuster and Van der Steen studied the biphasic HMF formation from fructose in water/MIBK solvent mixture in the presence of phosphoric acid (H_3PO_4) as a homogeneous catalyst.[13,14] The effects of temperature, fructose concentration, residence time, phosphoric acid concentration and MIBK/water ratio on the HMF selectivity and yield was investigated. The highest HMF yield of 69% at 94% fructose conversion was obtained with 1 M fructose and 0.1 M H_3PO_4 at 190 °C with an MIBK/water ratio value of 7.5 and a residence time of 5 min.

Activity of solid acid catalysts for fructose and glucose dehydration in MIBK/water system was studied by Fan et al. in a batch reactor with a solid heteropolyacid salt $Ag_3PW_{12}O_{40}$.[3] Effects of temperature and feedstock concentration on the activity of this catalyst for HMF production were investigated. The catalyst was found to be tolerant to high concentration of feedstock and could be recycled and retained high activity throughout the fructose conversion process. HMF yields as high as 77.7% and selectivity of 93.8% were reported from dehydration of fructose at 120 ºC for 60 min.[3]

In recent years some attention was paid to niobium compounds as solid acid catalysts to produce HMF from different feedstocks.[15,16] These compounds have proven to be interesting and important catalysts for various reactions in particular due to their high activity in the aqueous media.[5] Zhang et al. studied the performance of a series of porous niobium phosphate solid acid catalysts for conversion of glucose or glucose-united carbohydrates into HMF in pure water and water/MIBK solvent mixture.[17] They found that niobium phosphate catalyst contains both Lewis acid and Brønsted acid sites which are effective for isomerization of glucose to fructose and dehydration of fructose to HMF, respectively. Under optimum operating conditions and in the presence of a niobium phosphate catalyst, 33.2% and 39.3% HMF yield was obtained from glucose in pure water and water/MIBK solvents, respectively.[17] In another work by Carlini et al. dehydration of fructose, sucrose and inulin to HMF was studied by using niobium-based catalysts in aqueous medium. All the examined niobium catalysts were reported to display higher activity with respect to other heterogeneous systems under similar operating conditions.[18] H_3PO_4-treated niobic acid was found to have lower selectivity at high substrate conversion than niobium phosphate catalysts, which was attributed to the slightly higher Lewis and Brønsted acid sites for the niobium phosphate. Significant improvement in activity and selectivity of the catalysts was observed when HMF was extracted with MIBK from the aqueous media.[18]

So far, most of the HMF production reactions have been performed in batch reactors [3,5,12,19] or continuous stirred tank reactors (CSTR).[14,20,21] Continuous plug flow reactors (PFR) can offer lower operating costs and less environmental impacts of chemical production compared to the batch reactors.[22] They also have the capability of varying the reaction time and thus altering the product properties by changing the feeding flow rate and/or catalyst loading and could be a better mode for large scale operations. Few studies were reported on the continuous dehydration of hexoses into HMF using plug flow reactors in a single phase media [23] or a biphasic media in a microscale reactor with a homogeneous catalyst [22] or metal oxide particles as heterogeneous catalysts.[24] Since continuous-flow reactors are more desirable for industrial and commercial production, more comprehensive studies are needed to optimize the operating conditions for continuous production of HMF.

In the present study, we report the use of a novel continuous-flow tubular reactor designed and constructed in-house by the authors for biphasic dehydration of fructose to HMF using niobium compounds and ion exchange resins as solid acid catalysts. To the best of our knowledge, these catalysts have not been tested for fructose dehydration to HMF in a biphasic continuous-flow tubular reactor so far. The catalysts were comprehensively characterized through TGA, XRD, TPD-NH_3, BET/PSD, FT-IR and Py-FTIR analyses and their activities in terms of fructose conversion, HMF selectivity and yield, were examined. Effects of different operating conditions, such as reaction temperature, feeding flow rate, initial fructose concentration, aqueous to organic phase ratio (A/O) and phase transfer catalyst (PTC) on different catalysts, have been studied to find the best operating condition for HMF production with the maximum yield.

5.2 Materials and Methods

5.2.1 Materials

D-(-)-fructose (>99%), Amberlyst 15, Amberlyst 36, triethylamine (TEA), sodium chlorde (NaCl) and 5-hydroxymethylfurfural (99%, for preparing HPLC standard solution) were purchased from Sigma-Aldrich. Niobium pentoxide hydrate also called as niobic acid ($Nb_2O_5.nH_2O$) and niobium phosphate hydrate ($NbOPO_4.nH_2O$) were supplied by CBMM (Companhia Brasileira de Metalurgia e Mineraçã). HPLC grade water and acetonitrile for preparing the mobile phase for HPLC analysis as well as methyl isobutyl ketone (MIBK) were purchased from Caledon Laboratory Chemicals, and used as received.

5.2.2 Catalyst Preparation

In order to be able to use powder solid catalysts in a plug flow reactor as a catalytic packed bed, pelletization of the powder catalysts was performed. Niobium phosphate (thereafter named as NbP) and niobic acid (thereafter named as NbA) powders were humidified overnight and then were pressed in a pellet die by using hydraulic press at 10 tonnes/cm^2 of pressure to create pellets. The pellets were then crushed using a Wiley Mill and sieved and particles of sizes between 420-840 μm (Mesh No. 40 to Mesh No. 20) were collected and used for the experiments. Synthesized niobium phosphate (thereafter named as NbP-syn) and synthesized niobium sulfate (thereafter named as NbS-syn) were prepared by wet impregnation of 100 g niobic acid powder in 1 liter of phosphoric acid and sulfuric acid solutions in water (1 M), respectively. The solutions were mixed using a magnetic stirrer for 24 hours, then filtered and dried at 105 ºC in an oven overnight. The dried powders were then pelletized in the manner exactly same as that for the NbA and NbP to make the solid particles. Amberlyst 15 (thereafter named as Amb. 15) and Amberlyst 36 beads (thereafter named as Amb. 36) were used as received.

5.2.3 Continuous-Flow Reactor Setup and Experimental Procedure

The catalytic conversion of fructose to HMF was performed in a novel biphasic continuous-flow tubular reactor, schematically presented in Figure 5.1. The lab-scale tubular reactor setup was devised and constructed in-house for testing different heterogeneous solid catalysts as a fixed bed within the tubular reactor for conversion of sugars to HMF. For the experiments in this chapter, pure fructose solution in aqueous medium was used as the feedstock and MIBK was utilized as the extracting organic solvent. MIBK could continuously extract the produced HMF from the aqueous medium in-situ inside the fixed-bed catalytic reactor in order to enhance the HMF selectivity and yield by suppressing the side reactions of HMF in water. Sodium chloride (NaCl) was also added to the aqueous phase of feedstock as the phase transfer catalyst (PTC) to enhance the partition coefficient of HMF towards the organic phase (via the salting-out effect).

This reactor setup mainly consists of a vertical tubular reactor (SS-316 1/2" or 5/8" tubes - 30 cm long) seamlessly fitted inside a custom-manufactured bipartite solid aluminum column envelope adhered to a heat generator surface inside a column heater (Eppendorf CH-30). Herewith, aluminum was used as the material for the column envelope because of its high thermal conductivity to uniformly transfer the generated heat from the heater to the tubular reactor. In the column heater, the temperature of the heat generator surface is adjusted and controlled using a temperature controller (Eppendorf TC-50), hence the aluminum column envelope can keep the temperature constant and uniform along the tubular reactor.

In operation, appropriate amount of heterogeneous solid catalyst (particle size between 420-840 μm) is preloaded and supported inside the tubular reactor as a packed bed between two quartz wool plugs at the upper 2/3 length of the reactor (20 cm, reaction zone) while lower 1/3 length of the reactor (10 cm, pre-heating zone) remains empty to pre-heat the flowing biphasic media to the predetermined reaction temperature before entering the reaction zone. Two HPLC feeding pumps (SSI Mighty Mini Pump) connected to the bottom of the tubular reactor provide independent and adjustable flow rates of aqueous feedstock solution (containing substrate sugar, NaCl and water) and extracting organic solvent (pure MIBK) and then two phases are mixed in a tee union to provide a uniform upward rising flow of biphasic media through the tubular reactor. The temperature of the flowing biphasic media before and after passing the catalyst bed is also monitored using two thermocouples (Omega 1/8” K-type) located at upstream and downstream of the reaction zone (catalyst bed) inside the tubular reactor and connected to a digital thermometer. The pressure of the flowing media inside the reactor is adjusted and controlled using a back pressure regulator valve (Swagelok KBP Series) located on the exit line of the reactor and the pressure of the system is monitored on a pressure gauge.

In a typical run, after preloading a specific amount of the heterogeneous solid catalyst particles (depending on the bulk density of the catalyst to completely fill the reaction zone) inside the tubular reactor as a packed bed and assembling the reactor inside the column heater within the aluminum column envelope, the aqueous feedstock solution was pumped into the reactor using the dedicated feeding pump at a specific flow rate. When the reactor was filled up with the feedstock solution, the extracting organic solvent (MIBK) was pumped at a specific flow rate to the reactor concurrently. Then the pressure inside the reactor was increased to the desired pressure (typically 10 bars) using the back pressure regulator valve to avoid boiling of the water at the reaction temperatures above 100 ºC and the formation of vapor bubbles within the reactor system. The reactor was then heated up to the desired temperature after insulating the column heater and tubular reactor. After the reactor reached a stable temperature at the set-point and the steady state condition was achieved (depending on the feeding flow rate), samples were taken every hour, and each phase (aqueous and organic) fractionated from the sample was separately subjected to HPLC analysis. The concentrations of fructose and HMF in each phase were calculated from HPLC chromatographs in order to determine the fructose conversion as well as HMF selectivity and yield. The time on stream (TOS) for all of the experiments was 8 hours and no detectable soluble by-product or any other intermediate was found in the HPLC chromatographs.

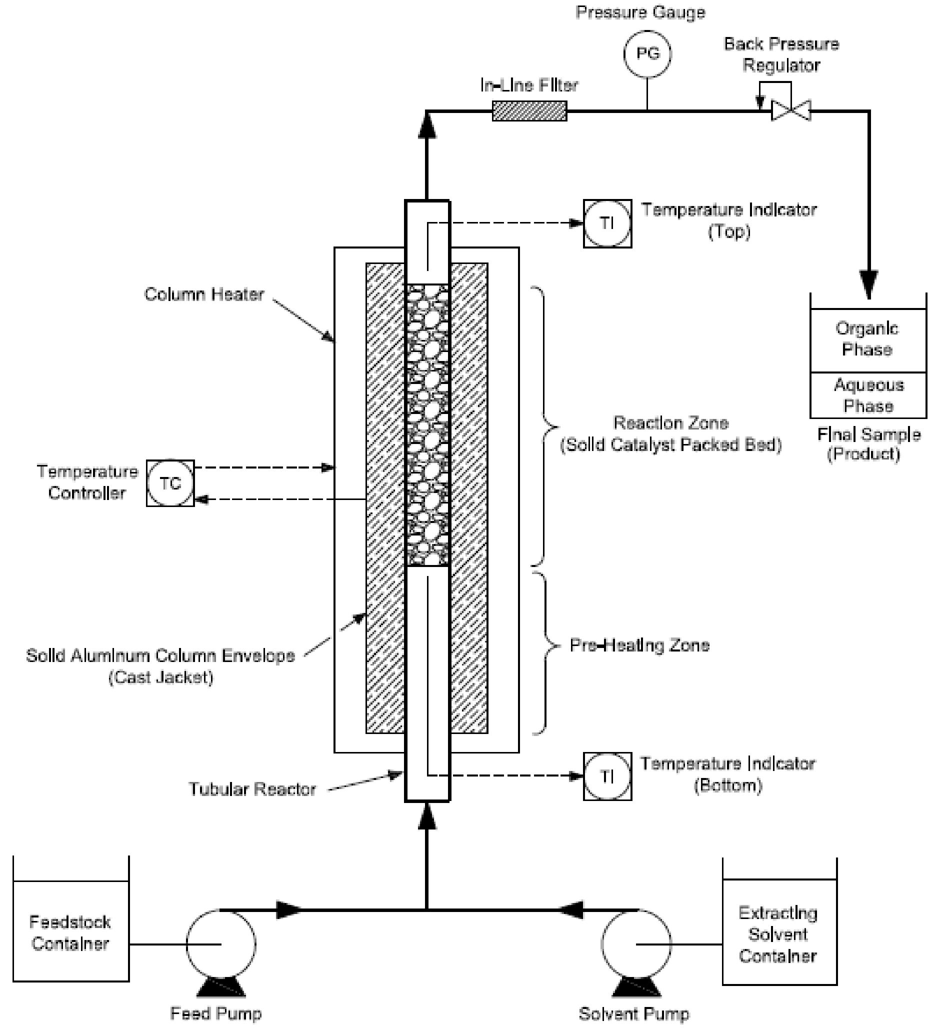

Figure 5.1: Schematic diagram of the biphasic continuous-flow tubular reactor system

5.2.4 Product Analyses

Each phase (organic and aqueous) of the product samples collected from the experiments was separately analyzed using an HPLC (Waters 2690 Separation Module) equipped with both RI detector (Waters 410 Differential Refractometer) with internal detector temperature of 35 ºC and UV detector (Waters 484 Tunable Absorbance Detector) set at 284 nm to determine the amount of feedstock (fructose) consumed and the amount of product (HMF) produced, respectively. Waters XBridge Amide column (3.5 µm, 4.6×250 mm) maintained at 35 ºC was used and the mobile phase was 75/25 acetonitrile/water (v/v) with 0.2 v% triethylamine (TEA) at the flow rate of 0.6 ml/min. The results for all experiments were analyzed by external calibration curves generated for fructose and HMF separately using standard solutions of fructose and HMF with known concentrations. The results are reported in terms of conversion, selectivity and yield, which are defined and calculated as follows:

$$\text{Fructose Conversion } (\%) = \frac{\text{Moles of fructose converted}}{\text{Initial moles of fructose}} \times 100\%$$

$$= \frac{\left[\left(C_{\text{Fru}}^{\text{aqu,F}} \times Q^{\text{aqu}}\right) - \left(C_{\text{Fru}}^{\text{aqu,P}} \times Q^{\text{aqu}}\right)\right] / M_{\text{Fru}}}{\left(C_{\text{Fru}}^{\text{aqu,F}} \times Q^{\text{aqu}}\right) / M_{\text{Fru}}} \times 100\% = \frac{C_{\text{Fru}}^{\text{aqu,F}} - C_{\text{Fru}}^{\text{aqu,P}}}{C_{\text{Fru}}^{\text{aqu,F}}} \times 100\% \qquad (5.1)$$

$$\text{HMF Selectivity } (\%) = \frac{\text{Total moles of HMF produced in both phases}}{\text{Moles of fructose converted}} \times 100\%$$

$$= \frac{\left[\left(C_{\text{HMF}}^{\text{aqu,P}} \times Q^{\text{aqu}}\right) + \left(C_{\text{HMF}}^{\text{org,P}} \times Q^{\text{org}}\right)\right] / M_{\text{HMF}}}{\left[\left(C_{\text{Fru}}^{\text{aqu,F}} \times Q^{\text{aqu}}\right) - \left(C_{\text{Fru}}^{\text{aqu,P}} \times Q^{\text{aqu}}\right)\right] / M_{\text{Fru}}} \times 100\% = \frac{\left[C_{\text{HMF}}^{\text{aqu,P}} + \left(C_{\text{HMF}}^{\text{org,P}} \times \frac{Q^{\text{org}}}{Q^{\text{aqu}}}\right)\right] / M_{\text{HMF}}}{\left(C_{\text{Fru}}^{\text{aqu,F}} - C_{\text{Fru}}^{\text{aqu,P}}\right) / M_{\text{Fru}}} \times 100\% \qquad (5.2)$$

$$\text{Total HMF Yield } (\%) = \frac{\text{Total moles of HMF produced in both phases}}{\text{Initial moles of fructose}} \times 100\%$$

$$= \frac{\left[\left(C_{\text{HMF}}^{\text{aqu,P}} \times Q^{\text{aqu}}\right) + \left(C_{\text{HMF}}^{\text{org,P}} \times Q^{\text{org}}\right)\right] / M_{\text{HMF}}}{\left(C_{\text{Fru}}^{\text{aqu,F}} \times Q^{\text{aqu}}\right) / M_{\text{Fru}}} \times 100\% = \frac{\left[C_{\text{HMF}}^{\text{aqu,P}} + \left(C_{\text{HMF}}^{\text{org,P}} \times \frac{Q^{\text{org}}}{Q^{\text{aqu}}}\right)\right] / M_{\text{HMF}}}{C_{\text{Fru}}^{\text{aqu,F}} / M_{\text{Fru}}} \times 100\% \qquad (5.3)$$

where,

$C_{\text{Fru}}^{\text{aqu,P}}$ is mass concentration of fructose in the aqueous feedstock solution (mg/ml),

$C_{\text{Fru}}^{\text{aqu,P}}$ is mass concentration of fructose in the aqueous phase of product sample (mg/ml),

$C_{\text{HMF}}^{\text{aqu,P}}$ is mass concentration of HMF in the aqueous phase of product sample (mg/ml),

$C_{\text{HMF}}^{\text{org,P}}$ is mass concentration of HMF in the organic phase of product sample (mg/ml),

Q^{aqu} is volumetric flow rate of the aqueous feedstock solution (ml/min),

Q^{org} is volumetric flow rate of the extracting organic solvent (ml/min),

M_{Fru} is molar mass of fructose (=180.16 g/mol),

M_{HMF} is molar mass of HMF (=126.11 g/mol).

5.2.5 Catalyst Characterization Methods

Brunauer-Emmett-Teller (BET) surface area as well as pore volume and pore size distribution (PSD) measurements were performed on a Micrometrics Tristar II 3020 series instrument. The samples were initially degassed under nitrogen flow for 8 hours at 110 ºC.

Crystalline phases and structure of the catalyst samples were investigated by X-ray diffraction (XRD) measurements on a PANalytical X'Pert Pro diffractometer using Cu-Kα radiation.

The total acidity of the catalysts was measured by temperature programmed desorption of ammonia (TPD-NH_3). TPD-NH_3 was carried out on a ChemBET Pulsar TPR/TPD automated chemisorption analyzer. In a typical experiment, about 100 mg of the catalyst sample was pretreated in a quartz reactor at 300 ºC for 1 hour under a flow of helium (99.9%, 120 ml/min) to remove the physically adsorbed compounds. After pretreatment, the sample was saturated with anhydrous ammonia at 100 ºC for 10 minutes and subsequently flushed with helium at the same temperature to remove any physisorbed ammonia. Then, TPD analysis was carried out by heating the catalyst sample from ambient temperature to 800 ºC with a heating rate of 10 ºC/min, during which the desorbed ammonia was measured by thermal conductivity detector (TCD) within the temperature range of 100 to 800 ºC.

Fourier transform infrared (FT-IR) spectrometry analyses of the catalyst samples were conducted on a PerkinElmer FT-IR spectrometer and the spectra were recorded in the region of 4000-550 cm^{-1}.

The FT-IR spectra with adsorbed pyridine (Py-FTIR) were obtained in the range of 1600-1400 cm^{-1}. Before the adsorption of pyridine, 1 g of each catalyst samples were heated in vacuum oven at 150 ºC overnight to be degassed and then cooled down to room temperature in a desiccator. 500 mg of each degassed sample was separated at this stage to be used as the background reference for the corresponding pyridine adsorbed sample. The other 500 mg of each samples were then treated with 500 μl of pyridine and degassed again in vacuum oven at 150 ºC for 4 hours to remove physically adsorbed pyridine. The spectra were recorded in the region of 1600-1400 cm^{-1} after the samples were cooled to ambient temperature. Brønsted to Lewis acid sites ratio (B/L) for each catalyst was evaluated by the ratio of the peak areas at 1540 cm^{-1} and 1445 cm^{-1} which have been attributed to the characteristic peaks for pyridine adsorbed on Brønsted acid and Lewis acid sites, respectively.[25]

Thermogravimetric analysis (TGA) of the fresh catalysts was conducted using a PerkinElmer Pyris 1 TGA in a nitrogen atmosphere. The samples were heated in a nitrogen flow at 20 ml/min from 40 ºC to 100 ºC at 10 ºC/min and then kept at 100 ºC for 10 min to remove the adsorbed moisture and volatile compounds. Then they were heated up to 700 ºC at heating rate of 10 ºC/min and the change in the sample weight by temperature is recorded. For the spent (used) catalyst, oxygen flow was used to burn the humins deposited on the surface of the catalysts. Derivative thermogravimetric (DTG) graphs were obtained from first derivative of TGA results with respect to time or temperature.

5.3 Results and Discussion

5.3.1 Characterization of Fresh Catalysts

The surface area and pore size distribution of the catalysts was measured by BET analyses. Table 5.1 provides a summary of the main characteristics of the studied catalysts including BET surface area and average pore size from BET analysis, Brønsted to Lewis acid sites ratio (B/L) from Py-FTIR analysis as well as total amount of acid sites from TPD-NH_3 analysis. Among the investigated catalysts, NbP has the highest BET surface area of 246 m^2/g and Amb. 15 and Amb. 36 have the lowest surface area of 51 and 30 m^2/g, respectively. However, the Amberlyst catalysts had larger average pores compared to the niobium based catalysts.

The catalysts crystalline structure was characterized by XRD. No diffraction peaks were observed on the XRD pattern suggesting that all fresh catalysts studied in this work are amorphous which is compatible with previous studies.[16,17,26]

Table 5.1: Properties of the fresh catalysts characterized by BET, Py-FTIR and TPD-NH_3

Catalysts	BET Surface Area (m^2/g)	Average Pore Diameter (nm)	Brønsted to Lewis Acid Sites Ratio	Total Amount of Acid Sites (mmol/g)
NbA	155	4	0.24	0.88
NbS-syn	108	5	0.24	0.86
NbP-syn	101	5	0.78	1.01
NbP	246	5	0.70	2.09
Amb. 15	51	29	N/A	-
Amb. 36	30	22	N/A	-

The total acidity and the strength of acid sites of the catalysts were determined by TPD-NH_3 analysis (Figure 5.2). This test was not performed for Amb. 36 and Amb. 15 as these catalysts decomposes at high temperatures during the analysis and does not result in correct data for TPD. This is also confirmed by TGA analysis which will be discussed later. Ammonia desorption profile of the catalysts could be divided into three regions corresponding to (1) weak (200-350 ^{o}C), (2) intermediate or medium (350-450 ^{o}C) and (3) strong (450-700 ^{o}C) acid strengths.

NbA and NbP-syn catalysts exhibited one broad peaks over a wide range of temperature from 140 to 350 ^{o}C and one smaller peak at around 435-445 ^{o}C with a shoulder at 520 ^{o}C which correspond to weak, moderate and strong acid sites, respectively. NbP-syn had an additional peak at 625 ^{o}C indicating the presence of stronger acid sites. NbS-syn exhibited one broad peak centered at 300 ^{o}C with a shoulder at 200 ^{o}C and two small and medium isolated peaks at 400 and 620 ^{o}C, respectively suggesting that this catalyst possesses weak and moderate acid sites as well as acid sites with strong strength. NbP exhibited the largest intensity for the peaks compared to other catalysts with three distinct peaks at 245, 420 and 700 ^{o}C corresponding to weak, moderate and strong acid sites, respectively. The total number of acid sites for the NbP catalyst (2.09 mmol/g) is much greater than those of NbP-syn (1.01 mmol/g), NbA (0.88 mmol/g) and NbS-syn (0.86 mmol/g) and hence the NbP catalyst shows more acidity/activity per unit mass in comparison with others (Table 5.1).

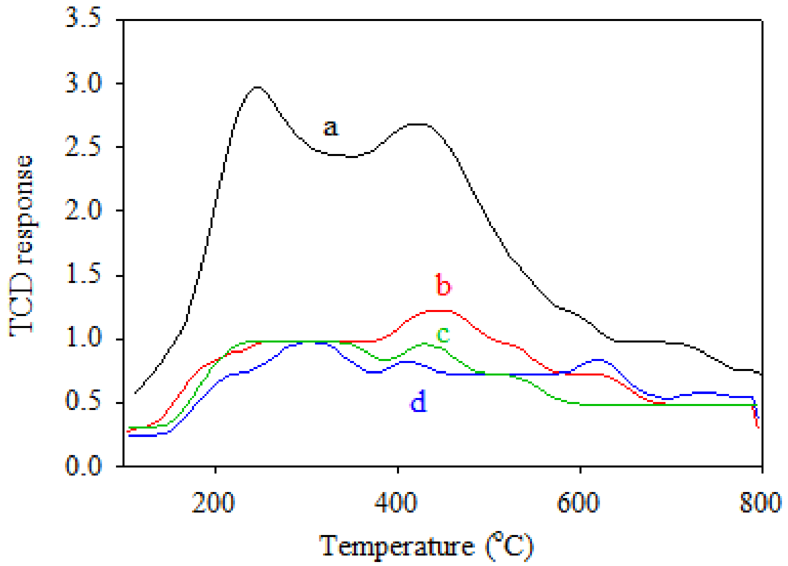

Figure 5.2: TPD-NH_3 profile for the fresh NbP (a), NbP-syn (b), NbA (c) and NbS-syn (d)

The FT-IR spectra of pyridine saturated samples are shown in Figure 5.3. The bending vibrations around 1445 cm^{-1} and 1540 cm^{-1} are assigned to Lewis and Brønsted acid sites, respectively and the peak at 1495 cm^{-1} is due to both Lewis and Brønsted acidity.[27] All of the niobium based catalysts show peaks at 1445 cm^{-1} with different intensities indicating the presence of Lewis acid sites. The intensity of this peak is the highest for NbA suggesting that this catalyst has the highest number of Lewis acid sites. The NbP, NbP-syn and NbS-syn show additional small peak at 1540 cm^{-1} suggesting that these catalysts have both Lewis acid and Brønsted acid sites. This peak has the highest intensity for NbP catalyst. The B/L ratio of these catalysts are in the sequence of NbP-syn > NbP > NbA = NbS-syn. The Amberlyst catalysts show just two peaks at 1540 and 1495 cm^{-1}, corresponding to pure Brønsted acid sites and mixed Lewis and Brønsted acidity on the surface of these catalysts. However, there is no peak at 1445 cm^{-1} for the Amberlyst catalysts indicating that these catalysts do not have pure Lewis acid sites.

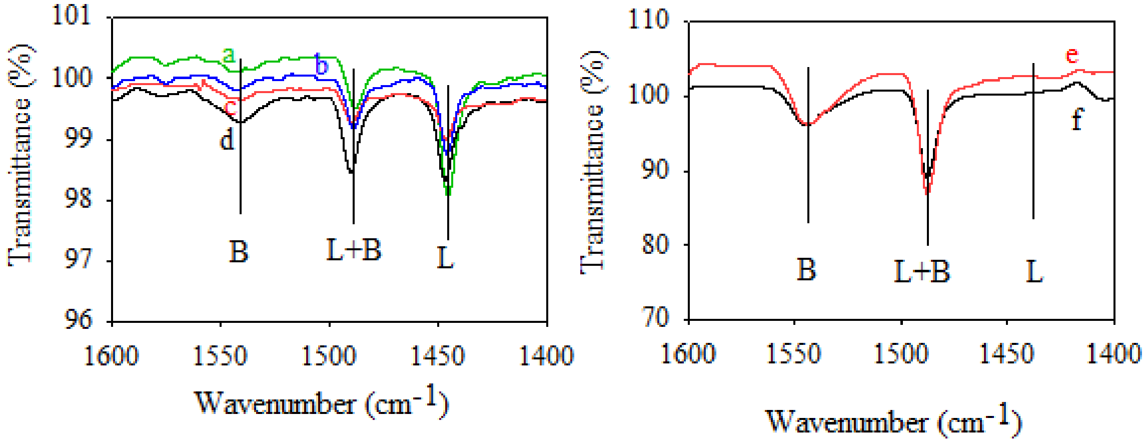

Figure 5.3: Py-FTIR spectra of the fresh NbA (a), NbS-syn (b), NbP-syn (c), NbP (d), Amb. 36 (e) and Amb. 15 (f)

Figures 5.4 and 5.5 show the TGA/DTG curves of Amberlysts and niobium based catalysts, respectively. According to Figure 5.4, Amb. 15 exhibited slightly larger total mass loss (66%), compared with Amb. 36 (61%). The mass loss of Amberlyst samples was composed of two steps for Amb. 36 and three steps for Amb. 15, which can be verified by the DTG curves of these two samples. The small peak seen in the DTG of both Amberlyst catalysts at temperatures up to 200 ºC is likely associated with the removal of physically adsorbed water. The second mass loss peak in the range of 200-350 ºC may be due to the depolymerization of polystyrene chains and decomposition of sulfonic groups. The mass loss peak above 350 ºC which is only seen in Amb. 15 can be attributed to the breakdown of polymer backbone and degradation of divinylbenzene [28].

According to Figure 5.5, among niobium based catalysts, NbP had the largest total mass loss (12.1%) compared to NbA (11.6%), NbP-syn (7.1%) and NbS-syn (6.7%). All of the niobium based catalysts showed a mass loss peak in the DTG curve between 100 to 200 ºC, likely due to the removal of water molecules coordinated to niobium atoms.[29,30]

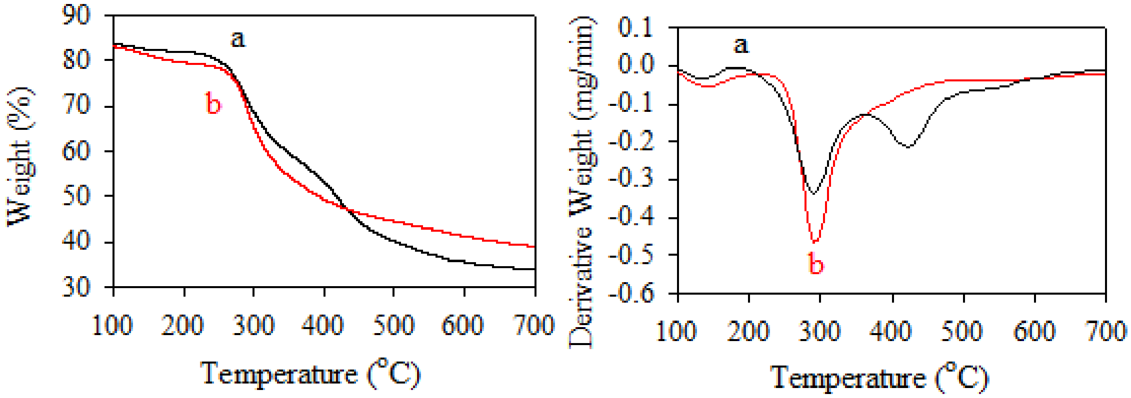

Figure 5.4: TGA/DTG graphs for the fresh Amberlyst 15 (a) and Amberlyst 36 (b)

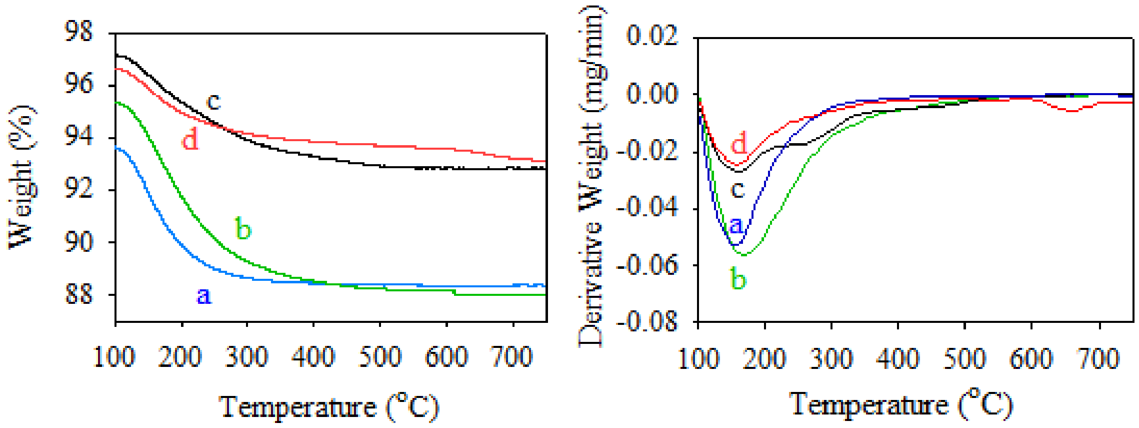

Figure 5.5: TGA/DTG graphs for the fresh NbA (a), NbP (b), NbP-syn (c) and NbS-syn (d)

The structure of the studied catalysts was also characterized by FT-IR analysis and is presented in Figure 5.6. All of the niobium based catalysts showed a broad O-H band absorption centered at 3400 cm^{-1} and a weak O-H band at 1620 cm^{-1} which can be assigned to the absorption of water. The niobium phosphate catalysts (NbP and NbP-syn) had stretching vibrations at around 1000 cm^{-1} that is attributed to the phosphate ion. This band is absent in NbA and NbS-syn catalysts as expected. Furthermore, the intensity of this peak is greater in NbP suggesting a higher P content in this catalyst.[16] The Amberlyst catalysts had a broad absorption centered at 3340 cm^{-1} due to the overlapping of O-H stretching vibration of water molecules and N-H stretch of amines. The IR absorption at around 1700 cm^{-1} represents the C=O stretching vibration. The asymmetric vibration of C-O-C aliphatic ether and stretching vibration of –CH_2OH groups can be observed at 1120 cm^{-1} and 1020 cm^{-1}, respectively.[31] The peaks observed between 670 cm^{-1} and 830 cm^{-1} are ascribed to the bending vibration of C-H out-of-plane.

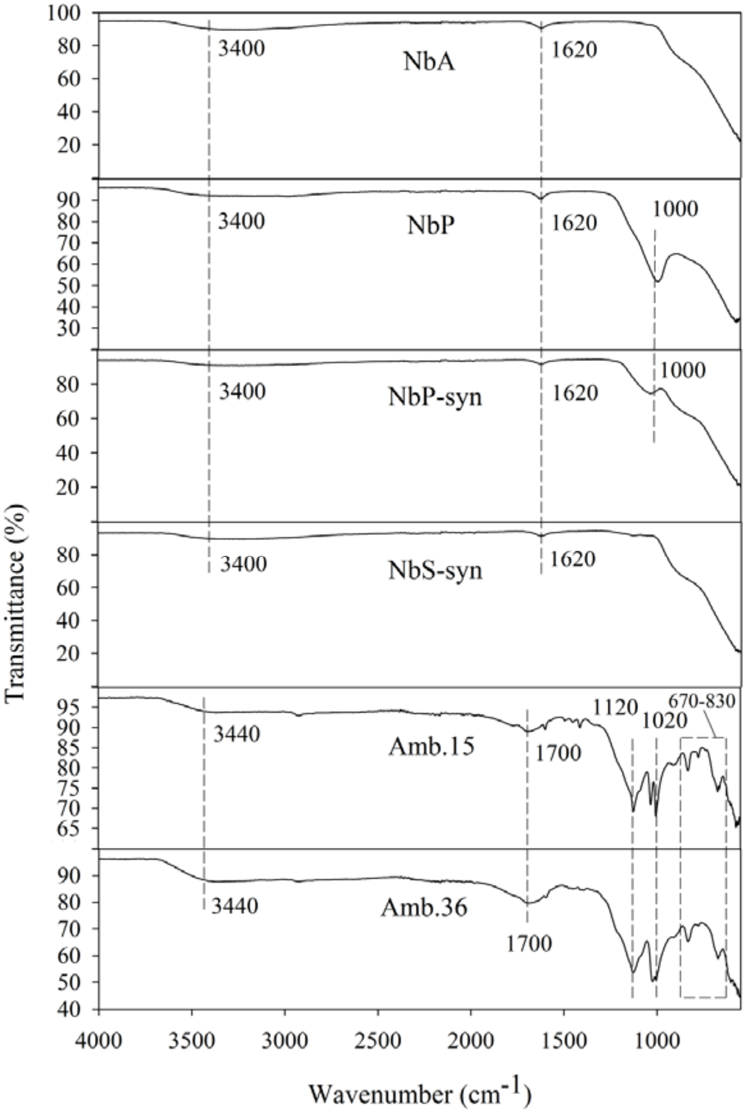

Figure 5.6: FT-IR spectra of the fresh catalysts

5.3.2 Catalytic Dehydration of Fructose to HMF

5.3.2.1 Effects of Feeding Flow Rate and Temperature in Single Aqueous Phase

For reference, catalytic fructose dehydration was first performed in single aqueous phase (using pure water solvent) in the presence of NbA (18 g catalyst loading). Table 5.2 shows the effects of feeding flow rate and temperature on fructose conversion, HMF selectivity and yield in single aqueous phase.

Table 5.2: Effects of feeding flow rate and temperature on fructose dehydration in single aqueous phase in the presence of NbA [a]

	1.0 ml/min (WHSV = 0.333 h^{-1})			0.5 ml/min (WHSV = 0.166 h^{-1})		
	80 °C	100 °C	120 °C	80 °C	100 °C	120 °C
Conversion (%)	19.7	52.8	65.9	32.0	64.0	73.9 ± 1.1
Selectivity (%)	3.1	8.4	11.0	3.8	9.6	11.8 ± 0.9
Yield (%)	0.6	4.4	7.3	1.2	6.2	8.7 ± 1.2

[a] Initial fructose concentration of 100 mg/ml (~10 wt%)

It can be seen that very low HMF selectivity and yield, less than 12% and 9%, respectively for both feeding flow rates, were obtained in pure water solvent due to the significant formation of side products (as indicated by the high conversion but low selectivity/yield). The main secondary reactions in aqueous media are the rehydration of HMF to levulinic and formic acids as well as polymerization of fructose and/or HMF to form humins.[32] With a constant flow rate (i.e., fixed WHSV), increasing temperature from 80 °C to 120 °C increased fructose conversion as well as the selectivity and yield. At a fixed temperature, fructose conversion, HMF selectivity and yield were also slightly enhanced by decreasing the flow rate from 1.0 to 0.5 ml/min (or reducing the WHSV from 0.333 h^{-1} to 0.166 h^{-1}) owing to the increased residence time of fructose inside the reactor. It has been commonly reported that fructose dehydration increased with increasing temperature and residence time.[3,15] Thus, higher temperatures (>100 °C) and lower feed flow rates (<1.0 ml/min) were further investigated in the rest of the experiments.

5.3.2.2 Effects of Feeding Flow Rate and Temperature in Biphasic Media

The performance of biphasic media on fructose dehydration was studied using MIBK as the extracting organic phase in the presence of NbA catalyst (18 g catalyst loading, same as the reference tests in single aqueous phase as discussed above) and NaCl as the phase transfer catalyst. The results are presented in Table 5.3. First the MIBK solvent flow rate was adjusted at 1.0 ml/min, while the aqueous feedstock flow rate was tested at 0.5 ml/min (i.e., aqueous to organic phase ratio of 1:2 (v/v)) containing 100 mg/ml fructose and 100 mg/ml NaCl.

Table 5.3: Effects of feeding flow rate, initial fructose concentration and reaction temperature on fructose dehydration in water-MIBK biphasic media in the presence of NbA catalyst

	WHSV = 0.166 h^{-1} [a]		WHSV = 0.333 h^{-1} [b]
	120 °C	130 °C	130 °C
Conversion (%)	88.3 ± 1.2	93.6	64.8 ± 0.8
Selectivity (%)	13.4 ± 0.8	17.7	34.8 ± 2.1
Yield (%)	11.9 ± 1.1	16.6	22.6 ± 2.8

[a] Initial fructose concentration of 100 mg/ml (~10 wt%), NaCl concentration of 100 mg/ml, Feeding flow rate of 0.50 ml/min, MIBK flow rate of 1.00 ml/min, A/O = 1:2 (v/v)

[b] Initial fructose concentration of 400 mg/ml (~40 wt%), NaCl concentration of 200 mg/ml, Feeding flow rate of 0.25 ml/min, MIBK flow rate of 1.25 ml/min, A/O = 1:5 (v/v)

Comparing the experimental results at 120 °C and 0.5 ml/min of feeding flow rate (WHSV = 0.166 h^{-1}) from Tables 5.2 and 5.3 shows that fructose conversion, HMF selectivity and yield in the biphasic system were all higher than those in the single aqueous phase. The results were further improved at a higher temperature of 130 °C in biphasic phase, while the rest of conditions were remained of no change (0.5 ml/min of aqueous feeding flow rate containing 100 mg/ml fructose and 100 mg/ml NaCl, and aqueous to organic phase ratio of 1:2 (v/v)), where the HMF selectivity and yield were increased to 18% and 17%, respectively. These results demonstrate the promoting effects of employing MIBK as an extracting organic solvent on conversion of fructose to HMF. It has been widely believed that the presence of an organic solvent can promote the dehydration reaction by extracting the HMF into organic phase immediately and suppressing the unwanted side reactions.[3,33]

The effects of biphasic system were further studied at 130 ºC and decreasing the aqueous to organic phase ratio (A/O) to 1:5 (v/v) through reducing the aqueous feeding flow rate to 0.25 ml/min and increasing the MIBK flow rate to 1.25 ml/min. Fructose and NaCl concentrations in the aqueous feed were also increased to 400 and 200 mg/ml, respectively. The results as presented in Table 5.3 indicate that using more extracting organic solvent (decreasing A/O ratio), more phase transfer catalyst and more concentrated feedstock has a positive effect on fructose dehydration reaction, resulting in significantly increased HMF selectivity and yield to 35% and 23%, respectively, although a lower fructose conversion (64.8%) was observed likely due to the decreased retention time (with a higher WHSV = 0.333 h^{-1}). For economic consideration, the feedstock solution should be as concentrated as possible. However, in practice a concentrated feedstock solution might lower the HMF selectivity due to higher rate of cross-polymerization and humins formation.[6,32] For instance, Fan et al. observed an initial raise followed by a drop in HMF selectivity when initial fructose concentration was increased from 10 wt% to 30 wt% and then to 50 wt%, where a continuous drop in conversion was observed when increasing the feed concentration from 10 wt% to 30 wt% and then to 50 wt%.[3]

Retention time of the reaction feed in the catalytic bed can be estimated by reciprocal of WHSV. A longer retention time can have a positive effect on fructose dehydration to HMF; however, very long retention times might also result in decomposition of HMF to other by-products, and subsequently lead to decreased yields and selectivity.[5,34] In the abovementioned experiments at 130 ºC the feedstock concentration was increased four times (from 100 mg/ml to 400 mg/ml) and aqueous feeding flow rate was reduced to half of the initial flow (from 0.50 ml/min to 0.25 ml/min). Since the same mass of catalyst (18 g) was used for both experiments, the WHSV for the experiment with 400 mg/ml of initial fructose concentration and 0.25 ml/min of aqueous feeding flow rate (WHSV = 0.333 h^{-1}) is twice as much as that of 100 mg/ml initial fructose concentration and 0.5 ml/min aqueous feeding flow rate (WHSV = 0.166 h^{-1}), which means that the retention time of the former test was half of that of the latter test. Longer retention/reaction time is in favor of higher conversion due to longer contact between reactant and catalyst inside the reaction zone of the reactor. Thus, there was a decrease in fructose conversion from 93.5 to 64.8%, while HMF selectivity and yield both improved to 35% and 23%, respectively. Similar observation with respect to effects of retention time was reported by Asghari and Yoshida as well as Lucas et al.[8,9] It should also be noted that using more extracting organic solvent by decreasing the A/O ratio from 1:2 to 1:5 (v/v) and using a higher concentration of phase transfer catalyst (NaCl) could also enhance the HMF selectivity and yield by suppressing side reactions (e.g., polymerization and rehydration of HMF) and formation of humins.[11,13,14]

Based on the above results, higher fructose concentrations in feedstock solution (400 mg/ml or ~40 wt%) and A/O of 1:5 (v/v) (feeding flow rate of 0.25 ml/min and MIBK flow rate of 1.25 ml/min) were selected and fixed for the rest tests of the study, unless stated otherwise.

5.3.2.3 Performance of Different Solid Acid Catalysts

Table 5.4 presents the fructose conversion, HMF selectivity and yield in the presence of various catalysts including NbA, NbS-syn, NbP-syn, NbP, Amb. 15 and Amb. 36, respectively, at 130 °C except for Amb. 15 (tested at 110 °C since the maximum recommended operating temperature for this catalyst is 110 °C).

Table 5.4: Performance of different solid catalyst in fructose dehydration at 130 °C [a]

	NbA	NbS-syn	NbP-syn	NbP	Amb. 15[b]	Amb. 36
Conversion (%)	64.8 ± 0.8	63.4 ± 1.1	79.8 ± 1.2	91.8 ± 1.5	35.1 ± 0.4	40.2 ± 1.0
Selectivity (%)	34.8 ± 2.1	35.0 ± 1.4	43.5 ± 0.5	37.6 ± 0.6	4.9 ± 1.8	10.1 ± 1.6
Yield (%)	22.6 ± 2.8	22.2 ± 1.9	34.7 ± 1.3	34.5 ± 1.6	1.7 ± 2.5	4.2 ± 2.6

[a] Initial fructose concentration of 400 mg/ml (~40 wt%), NaCl concentration of 200 mg/ml, Feeding flow rate of 0.25 ml/min, MIBK flow rate of 1.25 ml/min, A/O = 1:5 (v/v)

[b] The operating temperature for this catalyst was 110 °C

Niobium phosphate catalysts (NbP and NbP-syn) show a considerable high HMF yield (34%) and fructose conversion (79-91%), compared to 22% of HMF yield and 63-64% of fructose conversion with NbA and NbS-syn catalysts. The superior catalytic activity of niobium phosphate catalyst compared to niobic acid was also reported by Carniti et al. for dehydration of fructose to HMF in aqueous medium.[15] This could be related to the effective acidity in terms of number of acid sites as well Brønsted to Lewis acid sites ratio (B/L). According to Table 5.1, the total number of acid sites for NbP (2.09 mmol g^{-1}) and NbP-syn (1.01 mmol g^{-1}) is larger than those of NbA and NbS-syn (0.86-0.88 mmol g^{-1}), and they also have higher B/L ratios (0.70-0.78) compared with those of NbA and NbS-syn (0.24). As well known, Lewis and Brønsted acid sites are responsible for catalyzing the carbohydrates dehydration reaction to form aldehydes. Weingarten et al. reported xylose dehydration over solid acids, where the furfurals selectivity was reported to depend on the nature of the acid sites on the catalyst surface. Brønsted acid sites were shown to be more selective towards furfural production than Lewis acid sites.[35]

In our experiments, both NbP and NbP-syn catalysts showed almost the same activity in terms of HMF selectivity and yield which could be attributed to the high B/L ratio of these catalysts compared to the other catalysts tested in this work. However, the fructose conversion was found to be higher in the presence of NbP. This might be owing to its larger BET surface area (246 m^2/g) and more total number of acid sites (2.09 mmol g-1) than those of any other catalysts tested. The Amb. 15 and Amb. 36 catalysts gave very low fructose conversion (35-40%) and small HMF selectivity (5-10%) and yield (2-4%).

5.3.2.4 Effects of Reaction Temperature

The effects of reaction temperature (ranging from 110 to 150 ºC) on the activity of NbP, NbS-syn and Amb. 36 in terms of fructose conversion and HMF selectivity and yield were studied at feeding flow rate of 0.25 ml/min (WHSV = 0.428 h^{-1}), initial fructose concentration of 400 mg/ml (~40 wt%), NaCl concentration of 200 mg/ml and A/O = 1:5 (v/v). The results are shown in Figures 5.7 a, b and c.

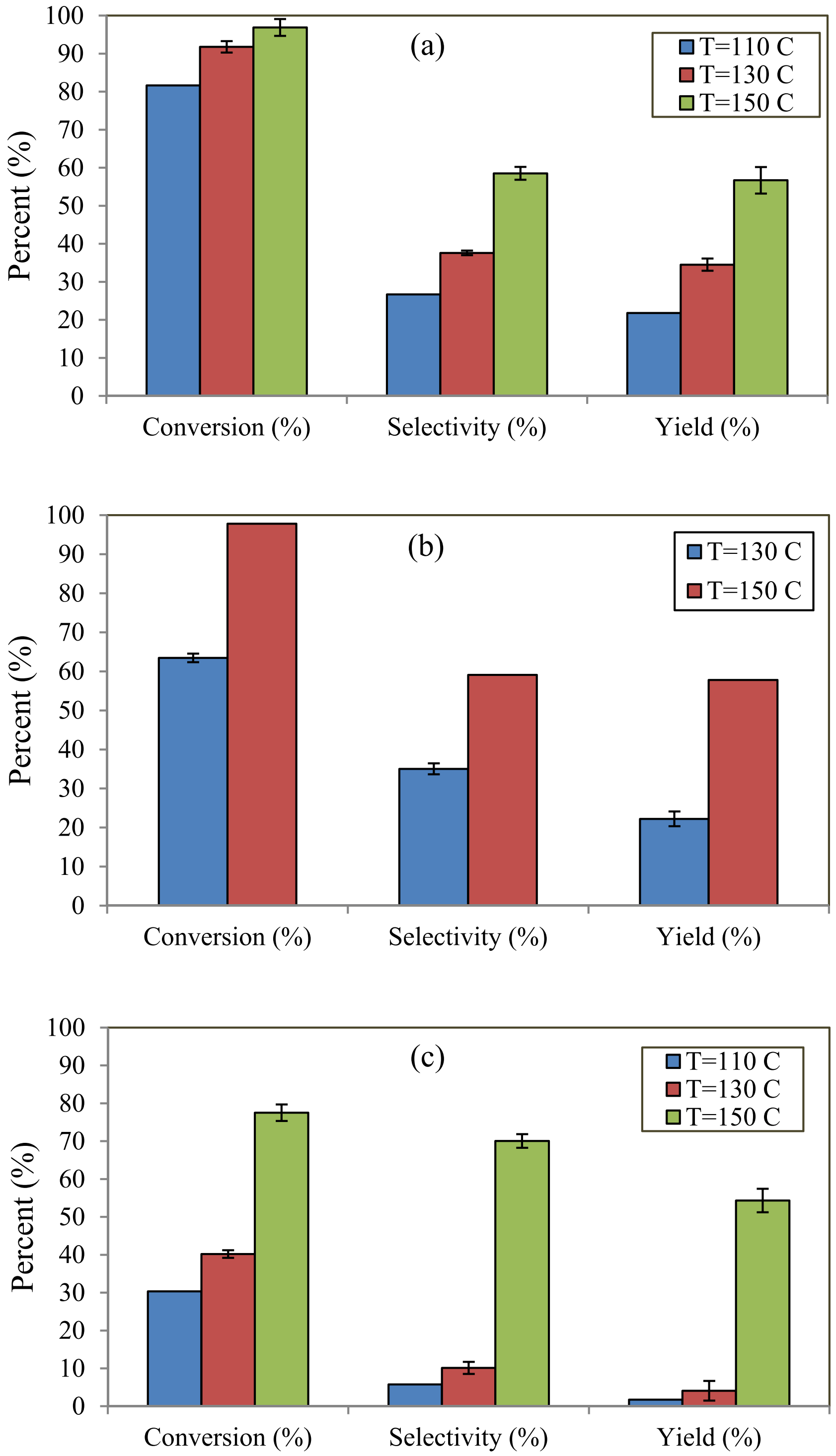

Figure 5.7: Effects of reaction temperature on the activity of NbP (a), NbS-syn (b) and Amb. 36 (c) (Feeding flow rate of 0.25 ml/min (WHSV = 0.428 h^{-1}), Initial fructose concentration of 400 mg/ml (~40 wt%), NaCl concentration of 200 mg/ml, A/O = 1:5 (v/v))

The results show that the activity of all catalysts improves with increasing temperature in terms of fructose conversion and HMF selectivity and yield. As expected, the fructose conversion was enhanced for all of the catalyst by increasing the temperature which is compatible with the previous results reported by other researchers [3,11,15], likely because endothermic heat effects of the carbohydrate dehydration reactions are thermodynamically favorable at a higher temperature. Surprisingly, there was drastic increases in fructose conversion, selectivity and yield with Amb. 36 catalyst while increasing temperature. For instance, the fructose conversion increased from 30.3% at 110 ºC to 77.5% at 150 ºC. Meanwhile, the HMF yield and selectivity also incremented as temperature increased, and the yields attained 54-57% at 150 ºC for all catalysts tested. The performance of the Amb. 36 is exceptionally good with respect to HMF selectivity at higher temperatures, the highest selectivity of 70.1% was obtained at 150 ºC with this catalyst. Due to its exceptionally high selectivity, Amb. 36 catalyst attained almost the same HMF yield at 150 ºC although with a lower conversion compared with the NbP and NbS-syn catalysts. This makes the Amb. 36 catalyst more favorable than the NbP and NbS-syn catalysts for dehydration of fructose to HMF from economics points of view.

5.3.2.5 Effects of Phase Transfer Catalyst (NaCl)

Under the reaction conditions of 400 mg/ml fructose concentration, 0.25 ml/min feed flow rate (WHSV = 0.428 h^{-1}), and A/O of 1:5 (v/v), the influence of NaCl as the phase transfer catalyst on dehydration of fructose was investigated using NbP as the catalyst. Figure 5.8 shows the results in the absence of NaCl and with 200 mg/ml NaCl at two different reaction temperatures (130 ºC and 150 ºC).

Fructose conversion with and without phase transfer catalyst remained almost constant (>90%). However, the HMF selectivity and yield both increased when NaCl was present in the aqueous feedstock solution and this increase became more evident at higher temperature (150 ºC). The similar results were reported by other researchers in dehydration of carbohydrates into HMF in a biphasic system.[36,37] Such results thus suggest that the presence of the inorganic salt in the aqueous feed contributed to the in-situ extraction of HMF from the aqueous phase to the organic phase, which would then suppress the side reactions and hence increasing the HMF selectivity and yield. With NbP catalyst and 200 mg/mL NaCl, fructose dehydration attained the highest selectivity and yield at 150 °C being 58.5% and 56.7%, respectively.

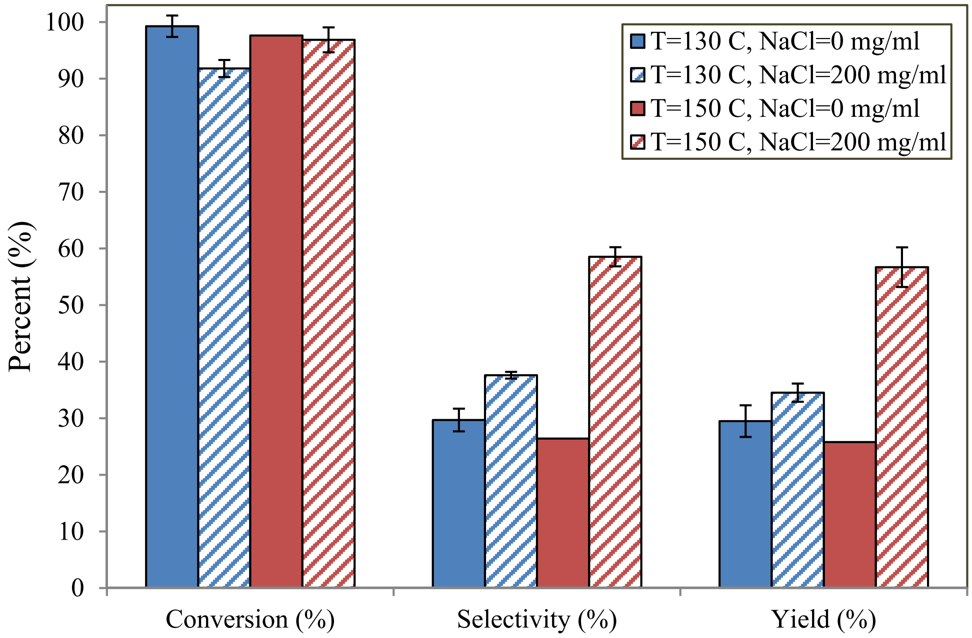

Figure 5.8: Effects of NaCl on the activity of NbP catalyst at 130 °C and 150 °C (Feeding flow rate of 0.25 ml/min (WHSV = 0.428 h^{-1}), Initial fructose concentration of 400 mg/ml (~40 wt%), A/O = 1:5 (v/v))

5.3.2.6 Effects of Catalyst Loading and Initial Fructose Concentration

According to previous studies, increasing the catalyst dosage could result in higher conversion due to the increase in residence time as well as the number of active sites.[9] However, it can also result in reduced HMF selectivity and yield due to the longer residence time that favors the side reactions, e.g., rehydration and polymerization of HMF and intermediates into levulinic acid and other by-products.[3,5] In our experiments the effects of catalyst loading and initial fructose concentration on the feedstock conversion and product selectivity and yield were studied by changing the amount of NbP and Amb. 36 catalysts and varying the initial fructose concentration in the aqueous feedstock solution.

The results for NbP catalyst are presented in Table 5.5. No significant change in the results was observed when the catalyst amount was reduced from 14 g to 7 g at 150 °C and 400 mg/ml initial fructose concentration (although the WHSV doubled or the residence time reduced to half). This indicates that there are sufficient catalytic sites available for the substrate (fructose) in the system even at lower catalyst dosage (7 g) and also the high catalyst dosage (14 g) did not show detrimental effects on the product selectivity and yield. On the other hand, with a fixed catalyst amount (7 g), when initial fructose concentration in the aqueous feedstock solution was reduced from 400 mg/ml to 200 mg/ml (i.e., reducing the WHSV to half or doubling the residence time), since a longer residence time favors the side reactions, HMF selectivity/yield dropped from 55% to 45%.

Table 5.5: Effects of catalyst loading and initial fructose concentration on the activity of NbP at 150 °C [a]

Catalyst Loading (g)	14 g	7 g	
Fructose Concentration (mg/ml)	400 [b]	400 [c]	200 [b]
Conversion (%)	96.9 ± 2.2	98.9 ± 1.9	99.7 ± 1.6
Selectivity (%)	58.5 ± 1.7	54.9 ± 3.1	45.1 ± 0.9
Yield (%)	56.7 ± 3.5	54.3 ± 3.5	44.9 ± 1.8

[a] Feeding flow rate of 0.25 ml/min, NaCl concentration of 200 mg/ml, A/O = 1:5 (v/v)
[b] WHSV = 0.428 h^{-1}
[c] WHSV = 0.856 h^{-1}

Table 5.6 shows the effects of catalyst dosage and initial fructose concentration on the performance of Amb. 36 at 150 °C, feeding flow rate of 0.25 ml/min, NaCl concentration of 200 mg/ml, and A/O ration of 1:5 (v/v). For this catalyst also reducing the initial fructose concentration from 400 mg/ml to 200 mg/ml with at a fixed amount of catalyst (14 g) and feeding flow rate (i.e., reducing the WHSV to half or doubling the residence time) resulted in a significant drop in HMF selectivity/yield from 70%/54% to 44.5%/32.8%. At a fixed fructose concentration (200 mg/ml), when catalyst loading was increased from 14 g to 24 g (i.e., reducing the WHSV by around 40% or increasing the residence time by around 40%), the fructose conversion increased from 73.6 to 91.9% as expected, while interestingly the HMF selectivity/yield were both increased drastically from 45%/33% to 65%/60%. Therefore, for Amb. 36, simply increasing the catalyst loading can effectively enhance the performance of the catalyst in catalytic dehydration of fructose into HMF.

Table 5.6: Effects of catalyst loading and initial fructose concentration on the activity of Amb. 36 at 150 °C [a]

Catalyst Loading (g)	14 g		24 g
Fructose Concentration (mg/ml)	400 [b]	200 [c]	200 [d]
Conversion (%)	77.5 ± 2.2	73.6 ± 1.5	91.9 ± 0.8
Selectivity (%)	70.1 ± 1.8	44.5 ± 2.7	64.8 ± 1.7
Yield (%)	54.3 ± 3.1	32.8 ± 3.3	59.6 ± 1.9

[a] Feeding flow rate of 0.25 ml/min, NaCl concentration of 200 mg/ml, A/O = 1:5 (v/v)
[b] WHSV = 0.428 h^{-1}
[c] WHSV = 0.214 h^{-1}
[d] WHSV = 0.125 h^{-1}

Based on the results as discussed above in this study, NbP, NbS-syn and Amb. 36 are the most active catalysts among all catalysts tested in this work, and the best operating conditions for catalytic dehydration of fructose to HMF in the continuous-flow reactor can be summarized as follows: temperature of 150 °C, aqueous feed flow rate 0.25 ml/min, organic (MIBK) flow rate 1.25 ml/min, fructose concentration in the aqueous feedstock solution 200 or 400 mg/ml, and NaCl concentration in the aqueous feedstock solution 200 mg/ml. Table 5.7 summarizes the activity of the three catalysts at the best operating conditions for production of HMF from fructose in the continuous-flow reactor. With these three catalysts (NbP, NbS-syn and Amb. 36) at the above best operating conditions, fructose dehydration in the continuous-flow reactor produced HMF at both a high selectivity (55-70%) and a high yield (54-60%).

Table 5.7: Catalytic activity of NbP, NbS-syn and Amb. 36 at the best operating conditions for production of HMF from fructose in the continuous-flow reactor

	NbP		NbS-syn	Amb. 36	
Catalyst Loading (g)	7	14	14	14	24
Fructose Concentration (mg/ml)	400 [a]	400 [b]	400 [b]	400 [b]	200 [c]
Conversion (%)	98.9 ± 1.9	96.9 ± 2.2	97.8	77.5 ± 2.2	91.9 ± 0.8
Selectivity (%)	54.9 ± 3.1	58.5 ± 1.7	59.1	70.1 ± 1.8	64.8 ± 1.7
Yield (%)	54.3 ± 3.5	56.7 ± 3.5	57.8	54.3 ± 3.1	59.6 ± 1.9

[a] WHSV = 0.856 h^{-1}
[b] WHSV = 0.428 h^{-1}
[c] WHSV = 0.125 h^{-1}

5.3.2.7 Catalyst Reusability Study

The possibility of reusing and recycling the catalysts was studied by testing the used Amb. 36 and NbS-syn at the above mentioned best operating conditions. After running the experiments for 8 hours of time on stream, the system was cooled down and washed by pumping distilled water through the reactor while the used catalysts were still packed inside. The reactor was then left overnight and it was again tested the next day with fresh feedstock and the used catalyst inside the reactor for another 8-hour time on stream and the results were compared with those achieved with the fresh catalysts (Table 5.8).

Table 5.8: Performance of the used catalysts of NbS-syn and Amb. 36 at 150 °C [a]

	NbS-syn [b]		Amb. 36 [c]	
	Fresh Catalyst	Used Catalyst	Fresh Catalyst	Used Catalyst
Conversion (%)	97.8	87.7 ± 2.1	91.9 ± 0.8	81.7 ± 2.2
Selectivity (%)	59.1	36.7 ± 1.8	64.8 ± 1.7	66.3 ± 0.8
Yield (%)	57.8	32.2 ± 2.9	59.6 ± 1.9	54.2 ± 2.5

[a] Feeding flow rate of 0.25 ml/min, NaCl concentration of 200 mg/ml, A/O = 1:5 (v/v)
[b] Catalyst dosage of 14 g, Initial fructose concentration of 400 mg/ml (WHSV = 0.428 h^{-1})
[c] Catalyst dosage of 24 g, Initial fructose concentration of 200 mg/ml (WHSV = 0.125 h^{-1})

The catalytic activity of the used NbS-syn was found to reduce compared to the fresh catalyst, resulting in lower fructose conversion and decreased selectivity and yield, which was likely due to the deposition of humins or other organic residues on the catalyst surface and the loss of active cites (acidity) and surface area of the catalyst. In contrast, the Amb. 36 catalyst showed a superb stability after 8 hours of time on stream, with even better selectivity and only a small decrease in fructose conversion and HMF yield. Therefore, Amb. 36 is expected to have a longer lifetime in real applications.

5.3.3 Characterization of Used Catalysts

In order to study the catalyst deactivation mechanism, used NbP catalysts from the experiments at 110 °C, 130 °C after 4 hours of time on stream at the best operating conditions (Feeding flow rate 0.25 ml/min, fructose conc. 400 mg/ml, NaCl conc. 200 mg/ml, A/O 1:5 (v/v)) were collected and analyzed by TGA in air to investigate the surface-adsorbed organic species that could lead to deactivation of the catalyst. Figure 5.9 shows the TGA and DTG graphs for fresh NbP catalyst and used catalysts after experiment at 110 °C and 130 °C.

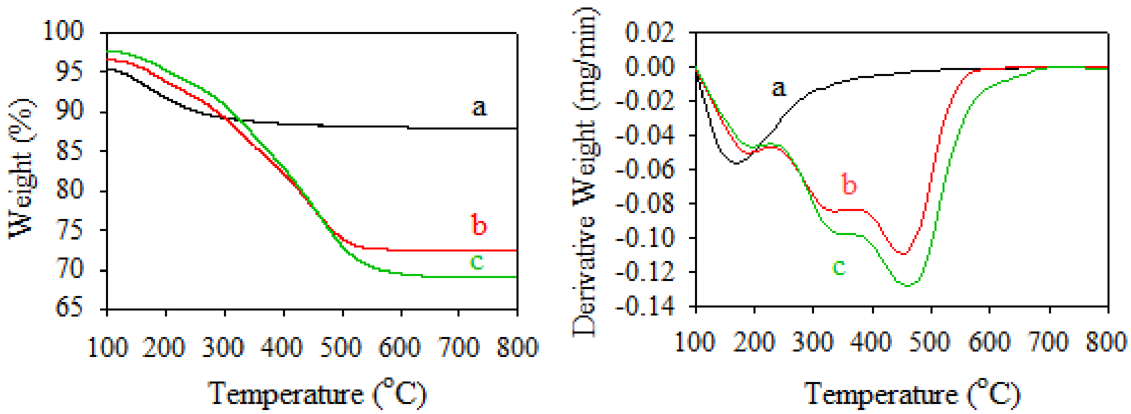

Figure 5.9: TGA/DTG graphs for the fresh NbP catalyst (a) and used NbP catalysts after experiments at 110 °C (b) and 130 °C (c)

According to the TGA graphs, much more weight loss was observed for the used catalyst samples and the weight loss increased with increasing the reaction temperature. The total mass loss of the fresh NbP catalyst was 7.4% compared to 24.0% for the used catalyst at 110 ºC and 28.6% for the used catalyst at 130 ºC. The weight loss difference may be attributed to deposition of insoluble organic species (humins, heavy oligomers and condensed polymers) on the surface of the catalyst particles during the reaction. As the reaction temperature increases, soluble humins and oligomers formed during fructose dehydration reaction would convert to insoluble humins and condensed polymers and grow on the catalyst surface as a function of temperature. Carniti et al. reported the similar trend for the TGA profiles of used NbP catalysts after reactions at various temperatures (110-130 ºC).[38] The DTG curves exhibits three distinct peaks: Peak 1 at 100-250 ºC corresponds to both volatile organic compounds and water molecules coordinated to niobium atoms,[29,30,38] Peaks 2 and 3 at 250-350 ºC and 350-700 ºC correspond to soft-coke and hard-coke formed from heavy oligomers and condensed polymers, respectively.[38]

5.4 Conclusions

The catalytic dehydration of fructose into HMF was investigated in a biphasic continuous-flow tubular reactor using different solid acid catalysts including niobium phosphate (NbP), niobic acid (NbA), synthesized niobium phosphate (NbP-syn), synthesized niobium sulfate (NbS-syn) Amberlyst 15 (Amb. 15) and Amberlyst 36 (Amb. 36). Some key conclusions are summarized as follows:

- It was demonstrated that HMF selectivity and yield from fructose were significantly higher in biphasic system than in a single aqueous phase.

- With the biphasic media, increasing the extracting organic solvent to aqueous phase ratio (or decreasing A/O), employing a phase transfer catalyst (NaCl) and using more concentrated feedstock had positive effects on fructose dehydration reaction, leading to significantly increased HMF selectivity and yield.

- At lower reaction temperatures (110 and 130 ºC), NbP and NbP-syn showed considerably higher activities than other catalysts tested, attributed to their larger total number of acid sites, higher Brønsted to Lewis acid sites ratio (B/L) and larger BET surface area.

- The activity of the catalysts improved with increasing temperature and this enhancement was surprisingly drastic for Amb. 36. With Amb. 36 while increasing the temperature from 110 °C to 150 °C, the fructose conversion increased from 30.3% to 77.5%, and HMF selectivity jumped from <6% to 70.1%.

- NbP, NbS-syn and Amb. 36 were the most active catalysts among all catalysts tested for dehydration of fructose to HMF.

- The best operating conditions for catalytic dehydration of fructose to HMF in the continuous-flow reactor are: temperature of 150 °C, aqueous feed flow rate of 0.25 ml/min, organic (MIBK) flow rate of 1.25 ml/min, fructose and NaCl concentrations in the aqueous feedstock solution of 200 or 400 mg/ml and 200 mg/ml, respectively.

- With these three catalysts (NbP, NbS-syn and Amb. 36) at the above best operating conditions, fructose dehydration in the biphasic continuous-flow tubular reactor produced HMF at both high selectivity (55-70%) and high yield (54-60%).

- The Amb. 36 catalyst showed a superb stability after 8 hours of time on stream, with even better selectivity and only a small decrease in fructose conversion and HMF yield. Therefore, Amb. 36 is expected to have a longer lifetime in real applications.

- The catalyst deactivation mechanisms were investigated by TGA analysis of the used NbP catalyst at different reaction temperatures, and the results evidenced that the deposition of insoluble humins on the surface of the catalyst particles is one of the main mechanisms for catalyst deactivation.

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Chapter 6

6 Catalytic Dehydration of Glucose to 5-HMF using Heterogeneous Solid Catalysts in a Biphasic Continuous-Flow Tubular Reactor

Abstract

This work aimed to produce 5-hydroxymethylfurfural (5-HMF) from glucose in a biphasic continuous-flow tubular reactor with various heterogeneous solid acid catalysts or combined solid acid-base catalysts. Among the catalysts tested, niobium phosphate (NbP) was found to be the most active catalyst for glucose dehydration with maximum HMF yield of 45% at 150 °C. The higher activity of NbP was attributed to its higher total number of acid sites and BET surface area as well as presence of both Lewis acid and Brønsted acid sites on the catalyst surface. The effects of different operating conditions such as aqueous to organic (A/O) phase ratio, reaction temperature and feeding flow rate on the activity of some selected catalysts were studied. Reducing A/O ratio by increasing the extracting organic phase flow rate and increasing the reaction temperature (up to 150 °C) were found to have positive effects on HMF production from glucose in the presence of NbP. Kinetics study demonstrated that the overall reaction of glucose dehydration to HMF over the NbP catalyst is a first-order reaction with the reaction rate constants (*k*) determined as 0.06, 0.21 and 0.6 min^{-1} at 110, 130 and 150 °C, respectively, and the apparent activation energy (E_a) calculated to be 77 kJ/mol.

Keywords: Glucose dehydration, 5-HMF, Biphasic continuous-flow tubular reactor, Niobium phosphate, Catalyst characterization, Catalyst stability, Glucose dehydration reaction kinetics

6.1 Introduction

The development of economically viable processes for production of biomass-derived fuels and chemicals has attracted intensive research efforts in recent years due to serious concerns over environmental issues and energy security related to our dependence on fossil fuels.[1,2] As one of the top bio-based platform chemicals, the five-membered ring compound, 5-hydroxymethylfurfural (HMF), is produced from acid-catalyzed dehydration of hexoses and can be transformed into a variety of important furan-based compounds.[1,3,4] For example, HMF can be oxidized to form 2,5-diformylfuran (DMF) as a promising biofuel with a higher energy density and boiling point than ethanol [2], and 2,5-furandicarboxylic acid (FDCA) and luvenic acid (LA) that are considered to be potential intermediates for the production of a variety of bio-based polymers and plastics.[2,5,6] Thus, in recent years, considerable efforts have been devoted on the transformation of carbohydrates into HMF.[6–15]

HMF could be produced at a high yield through the acid-catalyzed dehydration of fructose.[10,16] However, the key problem in application of fructose for HMF production is its high cost.[17] Another hexose, glucose, which is the monomer unit of cellulose, is more promising and important precursor for HMF as it offers a better economic value owing to its low cost and wide availability.[17] Nevertheless, conversion of glucose to HMF is usually associated with much lower yield and selectivity compared to that of fructose.[2] Fructose, as a ketohexose, can readily dehydrate to form HMF under mild acidic conditions, while dehydration of glucose, as an aldohexose, involves side reactions such as cross-condensation leading to formation of humins and oligomers/polymers as well as rehydration of HMF (forming levulinic and formic acids), resulting in lower HMF selectivity.[2]

In order to control the side reactions and improve HMF yields from glucose, researchers have investigated different methods including use of different organic solvents as the reaction media and different heterogeneous and homogeneous catalysts. For instance, Yan et al. employed solid acid catalysts such as SO_4^{2-}/ZrO_2 and $SO_4^{2-}/ZrO_2–Al_2O_3$ catalysts for conversion of glucose to HMF in dimethylsulfoxide (DMSO) as an organic solvent.[17] The reason for using the organic solvent was to suppress the undesirable side reactions. They reported that $SO_4^{2-}/ZrO_2–Al_2O_3$ catalyst with the Zr to Al molar ratio of 1:1 was the most active catalyst leading to the HMF yield of 47.6% within 4 hours of reaction at 130 ºC. They also performed a control experiment using fructose as the substrate and the results demonstrated that HMF formation from glucose does occurs via a two-step process of base-catalyzed glucose isomerization to fructose and acid-catalyzed fructose dehydration to HMF.[18]

Based on the two-step process mechanism for HMF formation from glucose, Takagaki et al. examined the use of a combination of solid base and acid catalysts for HMF formation from glucose.[19] Their experiments resulted in a successful HMF production from glucose in the reaction media of N,N-dimethylformamide in the presence of combined catalysts of Mg-Al hydrotalcite (HT) and Amberlyst-15 as a solid base and a solid acid, respectively, achieving 64% glucose conversion and 31% HMF selectivity at 100 ºC for 3 hours.

Fan et al. studied conversion of fructose and glucose into HMF and compared the activity of $Ag_3PW_{12}O_{40}$ containing both Lewis and Brønsted acid sites with pure Brønsted acid catalysts (HCl and $H_3PW_{12}O_{40}$), a pure moderated Lewis acid catalyst ($AgNO_3$), and $Cs_3PW_{12}O_{40}$ with no Brønsted and Lewis acidity, in a biphasic system consisting of methyl isobutyl ketone (MIBK) as the extracting organic solvent and water.[20] $Ag_3PW_{12}O_{40}$ exhibited the highest catalytic activity for glucose dehydration resulted in HMF yield of 76.3% at 130 ºC for 4 hours. This was attributed to the synergistic effect of the Lewis acid sites and Brønsted acid sites on this catalyst, and the use of MIBK extracting organic solvent that could effectively suppress unwanted side reactions by extracting HMF into the organic phase. Compared to the results of fructose dehydration, it was found that glucose dehydration requires a higher temperature, a larger amount of catalyst and a longer residence time.[20]

In another study, Nakajima et al. examined the activity of niobic acid ($Nb_2O_5.5H_2O$) as a heterogeneous Lewis acid catalyst for glucose dehydration in water at 120 ºC, compared with those of different homogeneous and heterogeneous Brønsted acids (HCl, H_2SO_4, Nafion NR50 and Amberlyst-15).[18] According to their results, the Brønsted acids catalysts did not produce much HMF but yielded more levulinic and formic acids under reaction conditions, which was attributed to the re-hydration of HMF catalyzed by Brønsted acids in water. Thus, Brønsted acid-catalyzed conversion of glucose to HMF in aqueous solutions is not selective.[21] In contrast, the use of the heterogeneous Lewis acid catalyst $Nb_2O_5.5H_2O$ resulted in 12.1% HMF yield which was further increased to 52.1% when H_3PO_4-treated niobic acid was used for the conversion of glucose into HMF in water.

Apart from the above efforts in using different catalysts and reaction media for higher HMF yield from glucose, there is still lack of knowledge regarding conversion rates of glucose. Some researchers have studied the kinetics of fructose or glucose dehydration to HMF in order to better understand the generic decomposition pathway and by-products formation.[5,22–24] Jing and Lü studied the kinetics of non-catalyzed conversion of glucose in water and proposed a first-order kinetics model to fit their experimental data.[25] From the kinetics analysis, they found that lower reaction temperatures are required to reduce the by-products formation. However, a higher temperature and shorter reaction time are required for higher HMF yield.[25] In another study by Wang et al. the kinetics of glucose dehydration catalyzed by various Lewis acid metal sites in a biphasic system was investigated, again assuming first-order reaction kinetics model.[26] The calculated activation energies using these catalysts were considerably lower than those of their Brønsted acid counterparts, suggesting different reaction mechanisms for the catalytic systems with different types of acid catalysts (Lewis or Brønsted acids).[26]

The present work aimed to study the catalytic dehydration of glucose into HMF in a biphasic media (water/MIBK) using a novel continuous-flow tubular reactor designed and constructed in-house by the authors. The catalytic activity of different solid acids (commercial niobium phosphate, Amberlyst 36, chromium phosphate and di-calcium phosphate) and combined solid acid-base catalysts (hydrotalcites with niobium phosphate or Amberlyst 36) were studied. To the best of our knowledge, these catalysts have not been tested for glucose dehydration to HMF in a biphasic continuous-flow tubular reactor so far. The catalysts were comprehensively characterized through various analyses including thermogravimetric analysis (TGA), X-ray diffraction (XRD), Brunauer-Emmett-Teller (BET) surface area and pore size distribution (PSD), Fourier transform infrared spectrometry (FT-IR) and pyridine adsorbed FTIR (Py-FTIR) and their activities in terms of glucose conversion, HMF selectivity and yield were examined. Effects of different operating conditions such as aqueous to organic phase ratio (A/O), reaction temperature and feeding flow rate on the activities of the catalysts have been studied. The data from the experiments at different temperatures and feeding flow rates were then used to study the kinetics of glucose dehydration reaction.

6.2 Materials and Methods

6.2.1 Materials

D-(+)-glucose (>99.5%), synthetic hydrotalcite (i.e., magnesium aluminum hydroxyl carbonate, $Mg_6Al_2(CO_3)(OH)_{16}.4H_2O$, Mg/Al molar ratio of 3:1), Amberlyst 36, triethylamine (TEA), sodium chloride (NaCl) and 5-hydroxymethylfurfural (99%, for preparing HPLC standard solution) were purchased from Sigma-Aldrich. Niobium phosphate hydrate ($NbOPO_4.nH_2O$) and commercial hydrotalcite PURAL MG30 (HT MG30) 5×5 cylindrical tablets (MgO/Al_2O_3 ratio of 30/70) were supplied by CBMM (Companhia Brasileira de Metalurgia e Mineraçã) and SASOL Germany GmbH, respectively. Calcium phosphate dibasic ($CaHPO_4$) and chromic phosphate ($CrPO_4$) were purchased from MP Biomedicals Company. HPLC grade water and acetonitrile for preparing the mobile phase for HPLC analysis as well as methyl isobutyl ketone (MIBK) were purchased from Caledon Laboratory Chemicals, and used as received.

6.2.2 Catalyst Preparation

As already mentioned in the previous chapters, pelletization of the powder catalyst was performed in order to enable using fine powders of solid catalysts in a plug flow reactor. Powder form niobium phosphate (thereafter named as NbP), chromic phosphate (thereafter named as CrP) and calcium phosphate dibasic (thereafter named as CaP) were humidified overnight and then were presses in a pellet die by using hydraulic press at 10 tonnes/cm^2 of pressure to create pellets. The pellets were then crushed using a Wiley Mill and sieved and particles of sizes between 420-840 μm (Mesh No. 40 to Mesh No. 20) were collected and used for the experiments. Cylindrical tablets of PURAL MG30 hydrotalcite sample (thereafter named as HT MG30) were also crushed using a Wiley Mill and sieved and particles of 420-840 μm in sizes (Mesh No. 40 to Mesh No. 20) were collected to be used as solid catalyst particles in the experiments. Amberlyst 36 (thereafter named as Amb. 36) was used as received.

For preparing the combined solid acid-base catalysts: Amb. 36/HT MG30 and NbP/HT MG30, equal amounts of each component were mixed to form a homogeneous mixture that was then used for the experiments. The combined niobium phosphate and activated synthetic hydrotalcite (NbP/HT-C-R) was prepared differently as the synthetic hydrotalcite (HT) should be initially calcined and rehydrated as an activation process. For that, equal amounts of HT and NbP powders were completely mixed together and calcined at 450 °C in a muffle furnace with the heating rate of 10 °C/min for 4 hours and then rehydrated by adding deionized water after cooling inside a desiccator to form a soft paste. The paste was dried overnight in an oven at 80 °C and then crushed using a mortar and pestle and sieved. Particles of sizes between 420-840 μm (Mesh No. 40 to Mesh No. 20) were collected and used as the combined solid acid-base catalyst (NbP/HT-C-R) for the experiments.

6.2.3 Continuous-Flow Reactor Setup and Experimental Procedure

The catalytic conversion of glucose to HMF was performed in a novel biphasic continuous-flow tubular reactor designed and constructed in-house by the authors. The schematic diagram and detailed description of this lab-scale tubular reactor setup as well as the experimental procedure have been presented in our previous work (Chapter 5). For the experiments in this chapter, 14 g of solid acid catalyst (or combined solid base-acid catalyst) was packed in the tubular reactor, and pure glucose solution in aqueous medium was used as the feedstock and MIBK was utilized as the extracting organic solvent. MIBK could continuously extract the produced HMF from the aqueous medium in-situ inside the fixed-bed catalytic reactor in order to enhance the HMF selectivity and yield by suppressing the side reactions of HMF in water. Sodium chloride (NaCl) was also added to the aqueous phase of feedstock as the phase transfer catalyst (PTC) to enhance the partition coefficient of HMF towards the organic phase (via the salting-out effect).

The time on stream (TOS) for all of the experiments was 8 hours except for some experiments which were continued for 24 hours to examine the catalyst stability and no detectable soluble by-product as well as fructose or any other intermediate was found in the HPLC chromatographs.

6.2.4 Product Analyses

Each phase (organic and aqueous) of the product samples collected from the experiments was separately analyzed using an HPLC system to determine the amount of feedstock (glucose) consumed and the amount of product (HMF) produced for calculation of glucose conversion, and HMF selectivity and yield. The detailed description of the HPLC system and analysis procedure as well as the definitions of conversion, selectivity and yield have been presented in our previous work (Chapter 5). To have a better understanding about the effectiveness of using extracting organic solvent (MIBK), in this work HMF yields in each phase (organic and aqueous) are also determined separately as follows:

$$\text{HMF yield in aqueous phase (\%)} = \frac{\text{Moles of HMF produced in aqueous phase}}{\text{Initial moles of glucose}} \times 100\% \qquad (6.1)$$

$$\text{HMF yield in organic phase (\%)} = \frac{\text{Moles of HMF produced in organic phase}}{\text{Initial moles of glucose}} \times 100\% \qquad (6.2)$$

6.2.5 Catalyst Characterization Methods

Catalyst samples were comprehensively characterized through various analyses including BET/PSD, Py-FTIR, XRD, TGA/DTG and FT-IR. The detailed description of these analytical facilities and analyses procedures have been presented in Chapter 5.

6.2.6 Kinetics Study Experiments

Kinetics study of glucose dehydration reaction was performed based on experiments in the presence of 14 g NbP catalyst with an aqueous feedstock solution containing 200 mg/ml glucose and 200 mg/ml NaCl. The experiments were carried out at three different temperatures (110 °C, 130 °C and 150 °C) and at a fixed temperature with various aqueous phase feeding flow rates of 0.25, 0.50, 0.75 and 1.00 ml/min (corresponding to WHSV 0.214, 0.428, 0.642 and 0.856 hr^{-1}, respectively) to obtain results for different lengths of contact/residence time. The contact time between the aqueous feedstock solution containing glucose substrate and the catalyst particles packed inside the reaction zone of the tubular reactor were calculated with respect to the catalyst bed voidage volume (the unfilled space between the solid particles of the catalyst packed-bed where the feedstock solution passes through) and the aqueous phase feeding flow rate. The effective bed voidage volume (10.9 cm^3) was determined by measuring the skeletal volume/density of the catalyst particles using water pycnometry method (4.9 cm^3 for 14 g catalyst particles) and taking into account the total volume of the reaction zone (catalyst bed) inside the tubular reactor (15.8 cm^3) which is calculated simply by internal diameter (ID) of the tubular reactor and the height of the catalyst pack-bed. Considering the volumetric flow rate of the aqueous feedstock solution and extracting organic solvent (aqueous to organic phase ratio of 1:5 (v/v)) and the effective bed voidage volume, and assuming a fully dispersed flow pattern for both immiscible phases inside the catalytic bed (reaction zone), the contact/residence times of the aqueous feedstock solution were calculated as 7.27, 3.63, 2.42 and 1.82 minutes for 0.25, 0.50, 0.75 and 1.00 ml/min feeding flow rates, respectively. The extracting organic phase (MIBK) flow rate was also varied with the feeding flow rate to keep the aqueous to organic phase ratio (A/O) constant at 1:5 (v/v). The glucose conversion profiles were analyzed at a fixed temperature and different flow rates (residence times) and the reaction rate constants (k) were calculated for different temperatures assuming the first-order kinetics for glucose conversion. Then the apparent activation energy (E_a) was determined using Arrhenius equation by calculated reaction rate constants at different temperatures.

6.3 Results and Discussion

6.3.1 Characterization of Fresh Catalysts

The surface area and average pore size distribution of the catalysts were determined by N_2 isothermal adsorption at 77 K, and the results are presented in Table 6.1. According to the results, NbP has the highest BET surface area of 246 m^2/g followed by Amb. 36 (30 m^2/g), CaP (5 m^2/g) and CrP (4 m^2/g). However, NbP has the smallest average pore size suggesting that this catalyst contains a larger fraction of finer pores than other catalysts tested.

Table 6.1: Textural properties of the fresh catalysts

Catalyst	BET Surface Area (m^2/g)	Average Pore Diameter (nm)	Total Pore Volume (cm^3/g)
NbP	246	5	0.31
CrP	4	13	0.01
CaP	5	16	0.02
Amb. 36	30	26	0.18

The FT-IR spectra of pyridine saturated samples (Py-FTIR) are shown in Figure 6.1. The bending vibrations around 1445 cm^{-1} and 1540 cm^{-1} can be assigned as Lewis and Brønsted acid sites, respectively, and the peak at 1495 cm^{-1} can be attributed to both Lewis and Brønsted acidity.[27] The NbP catalyst showed peaks at 1445 cm^{-1} and 1540 cm^{-1} suggesting the presence of both Lewis acid and Brønsted acid sites. The Brønsted to Lewis acid sites ratio (B/L) for this catalyst was found to be 0.70. The CrP and CaP catalysts did not show any peaks for Py-FTIR analysis indicating that these catalysts do not have any Lewis and/or Brønsted acid sites on the surface. Amb. 36 catalyst showed just two peaks at 1540 and 1495 cm^{-1}, suggesting that the catalyst contains only Brønsted acid sites on its surface.

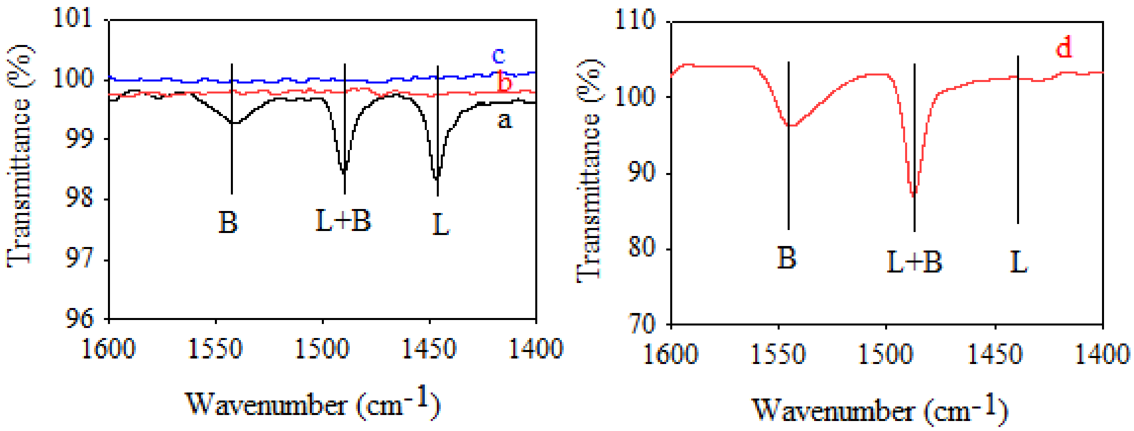

Figure 6.1: Py-FTIR spectra of the fresh NbP (a), CrP (b), CaP (c) and Amb. 36 (d)

The crystalline structure of the catalysts was analyzed by X-Ray diffraction measurements. No diffraction peaks were observed on the XRD pattern of all fresh catalysts, suggesting their amorphous nature, as also reported in many previous studies.[28–30]

The catalysts were also analyzed for thermal stability and their TGA/DTG graphs are shown in Figure 6.2.

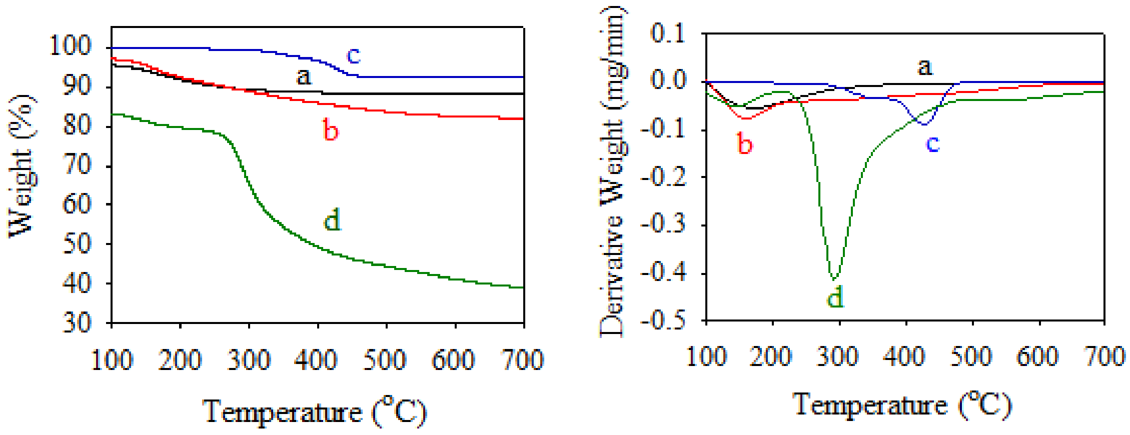

Figure 6.2: TGA/DTG graphs for the fresh NbP (a), CrP (b), CaP (c) and Amb. 36 (d)

According to the TGA graph, Amb. 36 is not thermally stable at temperature above. 250 °C, and gave the largest total mass loss at 300°C (60.9%), compared with NbP (12.1%), CrP (17.9%) and CaP (7.5%). The DTG curves showed a small mass loss peak in between 100 to 200 °C for NbP catalyst, likely corresponding to coordinated water molecules in the catalysts compounds.[31,32] This peak was also observed for CrP and Amb. 36 which was likely attributed to the removal of physically absorbed water. The large peak observed at around 290 °C for Amb. 36 suggests the de-polymerization of polystyrene chains and decomposition of sulfonic groups.[33] The CaP catalyst exhibited a peak at 425 °C with a small shoulder peak at 350 °C which may be attributed to the dehydration of CaP to calcium pyrophosphate ($Ca_2P_2O_7$).[34,35]

The molecular structure of the catalysts was also characterized by FT-IR analysis and the spectra are presented in Figure 6.3.

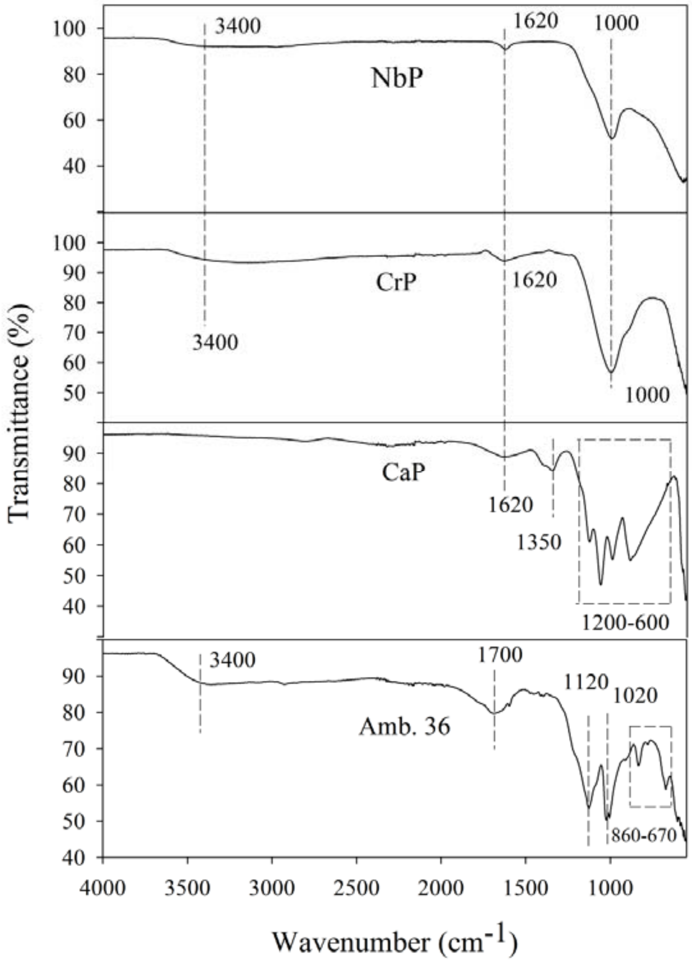

Figure 6.3: FT-IR spectra of the fresh catalysts

The NbP catalyst showed a broad O–H absorption with a low intensity centered at 3400 cm^{-1} and a weak O–H band at 1620 cm^{-1}, which can be assigned to the adsorbed water on the catalyst. Its spectrum also shows stretching vibrations at around 1000 cm^{-1} that can be attributed to the phosphate ion (PO_4^{3-}).[30] The CrP catalyst exhibited IR adsorption peaks at 3400 cm^{-1} and 1000 cm^{-1}, due to the O–H stretching and PO_4^{3-}, respectively.[36,37] The CaP catalyst exhibited small IR adsorption peaks at 1620 and 1350 cm^{-1}, attributed to the bending vibration of H–O–H and P–O–H in-plane, respectively, and the peaks between 1200 and 600 corresponding to the stretching vibration of P–O. The above observations are in good agreement with those reported in literature.[38,39] In the IR spectrum of Amb. 36, in addition to a broad absorption centered at 3400 cm^{-1} due to the overlapping of O–H stretching vibration of water molecules and N–H stretch of amines, absorption at around 1700 cm^{-1} 1120 cm^{-1} and 1020 cm^{-1}, representing the C=O stretching vibration, the asymmetric vibration of C–O–C aliphatic ether and stretching vibration of the –CH_2OH groups, respectively.[40] The peaks observed between 670 cm^{-1} and 860 cm^{-1} are ascribed to the bending vibration of C–H out-of-plane.

6.3.2 Catalytic Dehydration of Glucose to HMF

6.3.2.1 Performance of Different Solid Catalysts

Catalytic activity of NbP, CrP, CaP and Amb. 36 were compared for dehydration of glucose to HMF in biphasic continuous-flow tubular reactor. Also, inspired by the proposed reaction pathway for conversion of glucose to HMF which is assumed to proceed by isomerization of glucose to fructose (catalyzed by base catalyst) followed by dehydration of fructose to HMF (catalyzed by acid catalyst) [3,18], combined catalysts of solid base and acid were tested in order to examine the possible contribution of glucose isomerization to enhanced HMF formation. In our previous studies, activated hydrotalcite catalyst was found to have the highest selectivity in the isomerization reaction of glucose to fructose (Chapter 3), and Amb. 36 and NbP were found to be the most active catalysts for fructose dehydration reaction with considerably high HMF selectivity and yield (Chapter 5). Thus, three different solid acid-base combinations of these catalysts (Amb. 36/HT MG30, NbP/HT MG30 and NbP/HT-C-R) were tested for the glucose dehydration reaction.

The experiments were performed at the best operating conditions found for fructose dehydration (Chapter 5): reaction temperature of 150 °C, 0.25 ml/min aqueous feedstock flow rate containing 200 mg/ml (~20 wt%) glucose (WHSV = 0.214 h^{-1}) and 200 mg/ml NaCl as a phase transfer catalyst, and 1.25 ml/min extracting organic phase (MIBK) flow rate (i.e., A/O of 1:5 (v/v)). The results (glucose conversion, HMF selectivity and yield) with various catalysts are displayed in Table 6.2.

Table 6.2: Performance of different solid catalysts in glucose dehydration at 150 °C [a]

Catalyst	Conversion (%)	Selectivity (%)	HMF Yield (%)		
			Aqueous Phase	Organic Phase	Total
NbP	96.9 ± 1.5	38.8 ± 0.5	3.8 ± 0.5	33.8 ± 1.2	37.6 ± 1.7
CrP	51.3 ± 0.8	24.0 ± 0.1	1.2 ± 0.1	11.1 ± 0.4	12.3 ± 0.5
CaP	19.6	36.1	0.7	6.4	7.1
Amb. 36	32.0	21.8	0.7	6.3	7.0
Amb. 36/HT MG30	99.1	0.9	0	0.9	0.9
NbP/HT MG30	99.8	17.7	1.5	16.1	17.6
NbP/HT-C-R	99.8	7.4	1.2	6.2	7.4

[a] Initial glucose concentration of 200 mg/ml (~20 wt%), NaCl concentration of 200 mg/ml, Feeding flow rate of 0.25 ml/min, MIBK flow rate of 1.25 ml/min (A/O = 1:5 (v/v), WHSV = 0.214 h^{-1})

First of all, it should be mentioned that in all of the experiments, the isolated yield of HMF in the organic phase was found to be considerably higher than that in the aqueous phase, indicating the efficient extraction of HMF by MIBK into the organic phase.

From Table 6.2, NbP exhibited the highest HMF selectivity (38.8%) and yield (37.6%) compared with the other catalysts tested. The higher activity of NbP may be attributed to its higher total number of acid sites (2.09 mmol/g) and BET surface area (246 m^2/g) as well as presence of both Lewis acid and Brønsted acid sites on the catalyst surface (Table 6.1 and Figure 6.1). Niobium compounds such as niobic acid and niobium phosphate have been widely applied for dehydration of glucose or fructose, giving high HMF yields and high selectivity.[9,23,29,30] When compared with the results reported in the previous chapter for fructose dehydration at the same operating conditions (Chapter 5), both HMF selectivity and yield from glucose in the presence of NbP are lower, which is actually expected as it has been widely demonstrated that conversion of glucose to HMF is more difficult than conversion of fructose.[17,41] This may be attributed to the differences in the chemical structure of glucose and fructose as well as the possibility of two-step process (isomerization and dehydration) when glucose is used as the feedstock.[2,18]

Among the individual catalysts tested, Amb. 36 exhibited the lowest activity in terms of HMF selectivity (21.8%) and yield (6.9%). In a work by Zhang et al. the lower activity of Amberlyst catalysts compared to niobium phosphate was also reported.[29,30] The activity of Amb. 36 in terms of glucose conversion and HMF selectivity and yield was also found to be considerably lower than a previous study by the authors where Amb. 36 was used in fructose dehydration reaction at the same operating conditions (Chapter 5). Takagaki et al. reported similar observations by comparing the activity of Amberlyst-15 and other ion-exchange resins as catalyst for dehydration of glucose and fructose.[19] They found that fructose dehydration with Amberlyst-15 resulted in 73% HMF yield while no activity was observed for this catalyst in glucose dehydration to HMF. It was concluded that glucose dehydration over Amberlyst-15 produced anhydroglucoses (1,6-anhydro-β-D-glucopyranose and 1,6-anhydro-β-D-glucofuranose) rather than HMF.[19] This can be attributed to the absence of Lewis acid sites on the surface of Amberlyst catalysts (according to the Py-FTIR analysis results in Figure 6.1), while the Lewis acid sites are believed to be responsible for catalyzing the isomerization reaction of glucose to fructose.[26]

Although being less active than NbP catalyst, the CaP and CrP catalysts gave higher HMF selectivity and yield than Amb. 36. The difference in the catalytic activities of these catalysts could be attributed to their characteristics. According to Table 6.1, the BET surface area of CaP, CrP and Amb. 36 are almost in the same range (4-30 m^2/g), while the surface area of the NbP catalyst (246 m^2/g) was considerably higher than others, which might partially account for its superb activity for glucose dehydration. However, we believe that other catalyst properties such as total acidity and the strength and nature of the acid sites (Lewis and Brønsted acid sites) play more important role in the activity of the catalysts in dehydration of glucose or fructose to HMF.

The hypothesized reaction pathway for glucose dehydration reaction involves two steps: isomerization of glucose to fructose catalyzed by a base or Lewis acids, followed by the dehydration of fructose to HMF catalyzed by Brønsted acids.[26] Thus, Lewis acidity couples with Brønsted acidity could produce HMF from glucose with higher yields. According to the Py-FTIR results (Figure 6.1), both Lewis and Brønsted acid sites were observed in NbP catalyst, while none of these acid sites were observed in CrP and CaP catalysts, and only

Brønsted acid sites were detected in Amb. 36. This could explain the low activities of these catalysts (CrP, CaP and Amb. 36) for HMF production from glucose. In a study by Fan et al. it was also observed that the catalyst ($Ag_3PW_{12}O_{40}$) with both Lewis and Brønsted acid sites exhibited a much higher catalytic activity for glucose dehydration than other catalysts with pure Brønsted (HCl and $H_3PW_{12}O_{40}$) or Lewis ($AgNO_3$) acid sites or with none of these sites ($Cs_3PW_{12}O_{40}$).[20]

The combination of acid and base catalysts however did not show good activity in terms of selectivity and yield despite almost complete conversion (>99%) of glucose was attained, indicating the formation of large amount of by-products during the reaction. Different results were reported by Takagaki et al. with stepwise addition of HT and Amberlyst-15 catalysts in a batch reactor (achieving HMF selectivity as high as 76% and glucose conversion of 73%), where Amberlyst-15 was added to the reactor after 2.5 hours of the reaction with HT.[19] The poor activity of the mixed acid and base catalysts in our experiments might be due to the dilution of base sites by acid sites, and vice versa. It appears that critical levels of base/acid concentrations might be needed to enable the two-step process for dehydration of glucose into HMF, i.e., the base-catalyzed isomerization of glucose to fructose and the acid catalyzed dehydration of fructose to HMF.

We also conducted another experiment with equal amounts of NbP and HT MG30 catalysts packed in separated zones inside the tubular reactor (so that the feedstock solution containing glucose first passed through the HT MG30 base catalyst zone at the bottom of the reactor and then through the NbP acid catalyst zone at the top of the reactor) at the same operating conditions as the mixed catalysts at 150 ºC. The results were similar to the mixed base/acid catalysts suggesting that dehydration of glucose to HMF may not require co-presence of both base and acid catalysts, but the two-step isomerization-dehydration process is likely involved in the conversion of glucose to HMF catalyzed by Lewis acid and Brønsted acid sites, respectively. It also could be due to the high reaction temperature of 150 ºC which is not suitable for glucose isomerization to fructose over HT MG30 catalyst which led to formation of a large amount of humins by-product.

6.3.2.2 Effects of Aqueous to Organic Phase Ratio

NbP and CrP catalysts were tested at different aqueous to organic phase ratios (A/O). The aqueous feedstock solution flow rate in all of the tests was kept constant at 0.25 ml/min (WHSV = 0.214 hr^{-1}) while the flow rate of MIBK was adjusted at 0.50, 1.25 and 2.50 ml/min (corresponding to A/O of 1:2, 1:5 and 1:10 (v/v), respectively). For the NbP catalyst, the 1:10 ratio was also tested differently by reducing the feeding flow rate to 0.10 ml/min (WHSV = 0.086 hr^{-1}) and using MIBK flow rate of 1.00 ml/min. The results are shown in Table 6.3.

Table 6.3: Effects of aqueous to organic phase ratio (A/O) on the catalytic activity of NbP and CrP at 150 ^{o}C [a]

Catalyst	Flow rates (ml/min)		A/O Ratio	Conversion (%)	Selectivity (%)	HMF Yield (%)		
	Aqueous Phase	Organic Phase				Aqueous Phase	Organic Phase	Total
NbP	0.25	0.50	1:2	96.5 ± 0.9	29.7 ± 2.1	6.3 ± 1.5	22.4 ± 0.7	28.7 ± 2.2
NbP	0.25	1.25	1:5	96.9 ± 1.5	38.8 ± 0.5	3.8 ± 0.5	33.8 ± 1.2	37.6 ± 1.7
NbP	0.25	2.50	1:10	99.4 ± 0.2	45.2 ± 1.1	2.3 ± 0.3	42.6 ± 0.7	45.0 ± 1.0
NbP	0.10	1.00	1:10	100	17.5	1.7	15.8	17.5
CrP	0.25	1.25	1:5	51.3 ± 0.8	24.0 ± 0.2	1.2 ± 0.1	11.1 ± 0.4	12.3 ± 0.5
CrP	0.25	2.50	1:10	48.4 ± 0.7	28.7 ± 2.2	0.7 ± 0.5	13.2 ± 0.4	13.9 ± 0.9

[a] Initial glucose concentration of 200 mg/ml (~20 wt%), NaCl concentration of 200 mg/ml

Previous studies showed that decreasing A/O had a beneficial effect and led to higher yield and selectivity.[42–44] According to Table 6.3, our results for both NbP and CrP catalysts are in good agreement with previous findings and show an increasing trend in HMF selectivity and yield when the MIBK flow rate was increased from 0.50 to 1.25 and 2.50 ml/min (A/O of 1:2, 1:5 and 1:10 (v/v), respectively), indicating that side reactions are suppressed in presence of higher amount of MIBK as the extracting organic solvent.

In the experiments using NbP catalyst and the A/O of 1:10 with aqueous phase flow rate of 0.25 ml/min and organic phase flow rate of 1.25 ml/min, complete glucose conversion (100%) and a very high HMF yield (45%) were achieved. When the aqueous and organic phases flow rates were decreased to 0.10 and 1.00, respectively (keeping the same A/O of 1:10), however a drop in HMF selectivity and yield was observed. This likely resulted from too long retention time of the aqueous feedstock phase (a much lower WHSV) as well as the organic phase inside the reactor due to the lower flow rates. This could promote the side reactions to degrade the HMF or self-polymerize the reaction intermediates to humins, leading to a reduction in HMF selectivity and yield.[16]

6.3.2.3 Effects of Feeding Flow Rate and Temperature

The effects of reaction temperature and feeding flow rate on glucose dehydration reaction were tested in the presence of NbP at three different reaction temperatures of 110, 130 and 150 ºC and four feeding flow rates of 0.25, 0.50, 0.75 and 1.00 ml/min for each temperature. The organic phase flow rate was also adjusted accordingly to keep the A/O of 1:5 (v/v). Considering that the initial glucose concentration was 200 mg/ml and 14 g catalyst was used for all of the experiments, the feeding flow rates of 0.25, 0.50, 0.75 and 1.00 correspond to WHSV of 0.21, 0.43, 0.64 and 0.86 hr^{-1}, respectively. The results of the glucose conversion and HMF yield in the presence of NbP catalyst at different reaction temperatures and feeding flow rates are presented in Figure 6.4.

It is clearly observed that at a fixed temperature, increasing the feeding flow rate from 0.25 to 1.00 ml/min (i.e., decreasing retention time of the substrate inside the reactor) results in lower glucose conversions and consequently lower HMF yields. On the other hand, at a constant feeding flow rate, increasing the reaction temperature showed a positive effect on the glucose conversion and HMF yield. The highest glucose conversion (97%) and HMF yield (37.7%) in the presence of NbP were obtained at 150 ºC with 0.25 ml/min feeding flow rate and 1.25 ml/min MIBK flow rate (A/O = 1:5 (v/v)). Positive effects of reaction temperature on the dehydration reaction were also reported by Qi et al. for conversion of fructose to HMF [44], as well as in our previous work on fructose dehydration (Chapter 5).

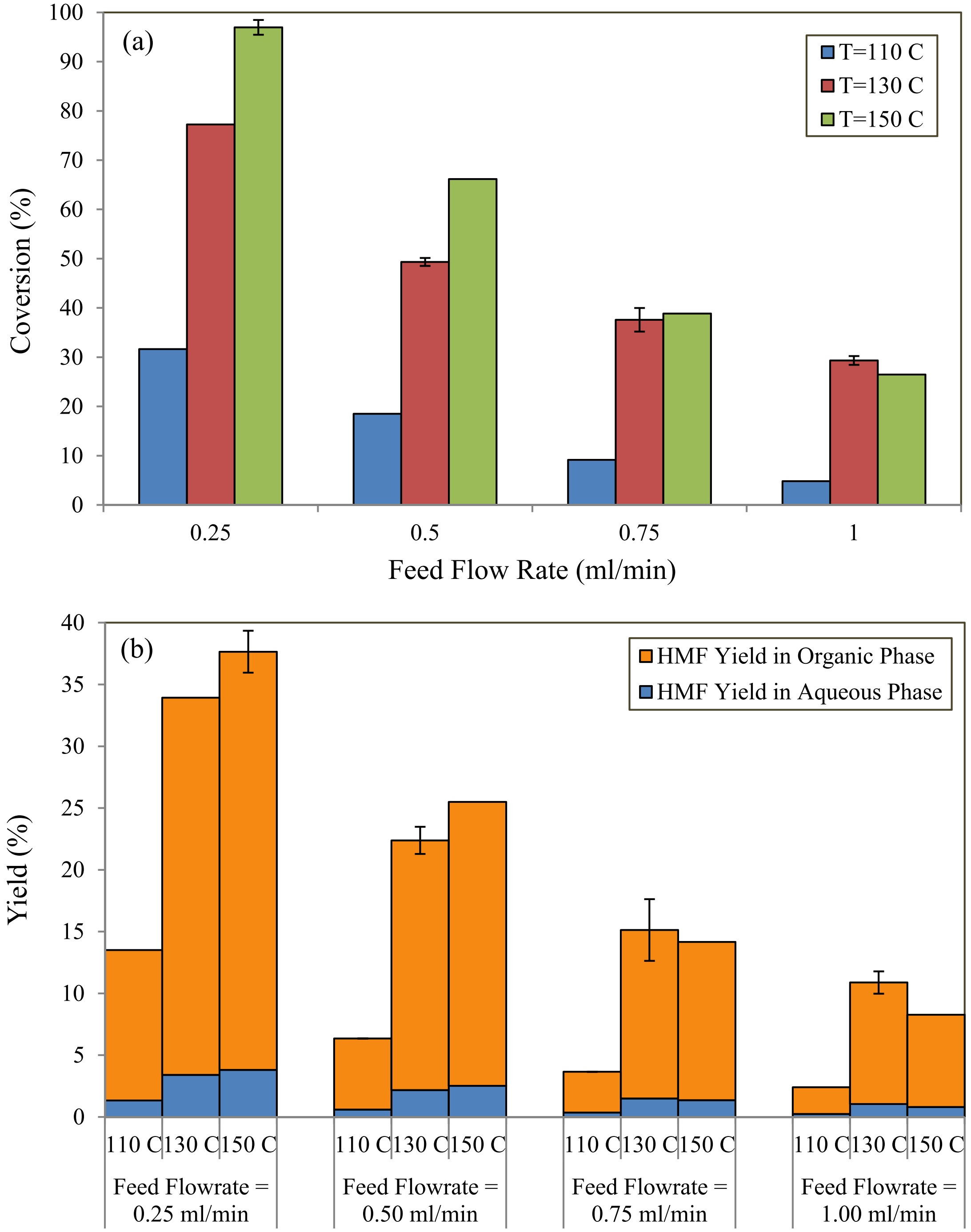

Figure 6.4: Effects of different reaction temperatures and feeding flow rates on the activity of NbP catalyst for glucose dehydration with respect to glucose conversion (a) and HMF yield (b) (Initial glucose concentration of 200 mg/ml, NaCl concentration of 200 mg/ml, A/O = 1:5 (v/v))

According to Figure 6.4 b, one can see that in all of the experiments the isolated yield of HMF in the organic phase was considerably higher than that in the aqueous phase (9-11 times) indicating the efficient extraction of HMF by MIBK into the organic phase.

6.3.2.4 Kinetics Study

Kinetics analysis was performed on the glucose dehydration reaction over the NbP catalyst in the continuous-flow reactor. The obtained results from the experiments with NbP catalyst as reported in the previous section were used to model the kinetics of glucose conversion. In order to find the reaction rate constants (*k*) at different temperatures (110, 130 and 150 °C), glucose concentrations were measured in the aqueous product stream in a fixed reaction temperature and different feeding flow rates (0.25, 0.50, 0.75 and 1.00 ml/min) to obtain different reaction/retention times. In accordance to the literature work, a first-order reaction kinetics model was commonly adopted for the overall glucose dehydration reaction.[25,26] For a packed bed continuous-flow reactor assuming constant volumetric flow rate (v_0), the molar balance equation is as follows:

$$\frac{F_{A0} \cdot dX_A}{dW} = -r_A' \tag{6.3}$$

where F_{A0} (mol.s^{-1}) is the entering molar flow rate of species A, X_A (-) is conversion of A, W (kg) is the weight of catalyst bed, and r_A' (mol.s^{-1}.kg^{-1}) is the reaction rate with respect to kg of the catalyst, which can be obtained by:

$$F_{A0} = C_{A0} v_0 \tag{6.4}$$

$$X_A = \frac{v_0 C_{A0} - v_0 C_A}{v_0 C_{A0}} = \frac{C_{A0} - C_A}{C_{A0}} \tag{6.5}$$

$$W = \rho_b V \tag{6.6}$$

$$r_A' = r_A / \rho_b \tag{6.7}$$

where C_{A0} (mol.L^{-1}) is the initial molar concentration of species A in the feedstock solution, C_A (mol.L^{-1}) is the molar concentration of species A in the product stream at any time (*t*),

v_0 ($L.s^{-1}$) is the volumetric flow rate of the feedstock solution containing species A, ρ_b ($kg.L^{-1}$) is the catalyst pack-bed bulk density and V (L) is the total bed volume.

Substituting equations (6.4) ~ (6.7) into equation (6.3), one has:

$$\frac{(C_{A0}v_0)d\left(\frac{C_{A0}-C_A}{C_{A0}}\right)}{d(\rho_b V)} = -\left(\frac{r_A}{\rho_b}\right) \tag{6.8}$$

Rearranging it, one has:

$$\frac{dC_A}{dV/v_0} = r_A \quad \text{or} \quad \frac{dC_A}{dt} = r_A \tag{6.9}$$

For simplicity, let $C = C_A$ (glucose initial concentration) and $r_A = r$ taking the unit of ($mg.ml^{-1}$) and ($mg.ml^{-1}.min^{-1}$), respectively. Applying the first-order reaction rate law (i.e., $-r = kC$), one has:

$$-r = -\frac{dC}{dt} = kC \tag{6.10}$$

Integration of the above equation, one has:

$$-\ln\left(\frac{C}{C_0}\right) = kt \tag{6.11}$$

where, r is the reaction rate ($mg.ml^{-1}.min^{-1}$), k is the reaction rate constant (min^{-1}), C is the glucose concentration in the aqueous product stream ($mg.ml^{-1}$), C_0 is the initial glucose concentration in the aqueous feedstock solution ($mg.ml^{-1}$) and t is the reaction/retention time (min). The reaction rate constant (k) for each temperature was determined by plotting $-ln\ (C/C_0)$ versus t (slope of the line) as shown in Figure 6.5. The acceptable linear trend (linear correlation coefficient R^2 between 0.979 to 0.998) supports the first-order assumption for the reaction order.

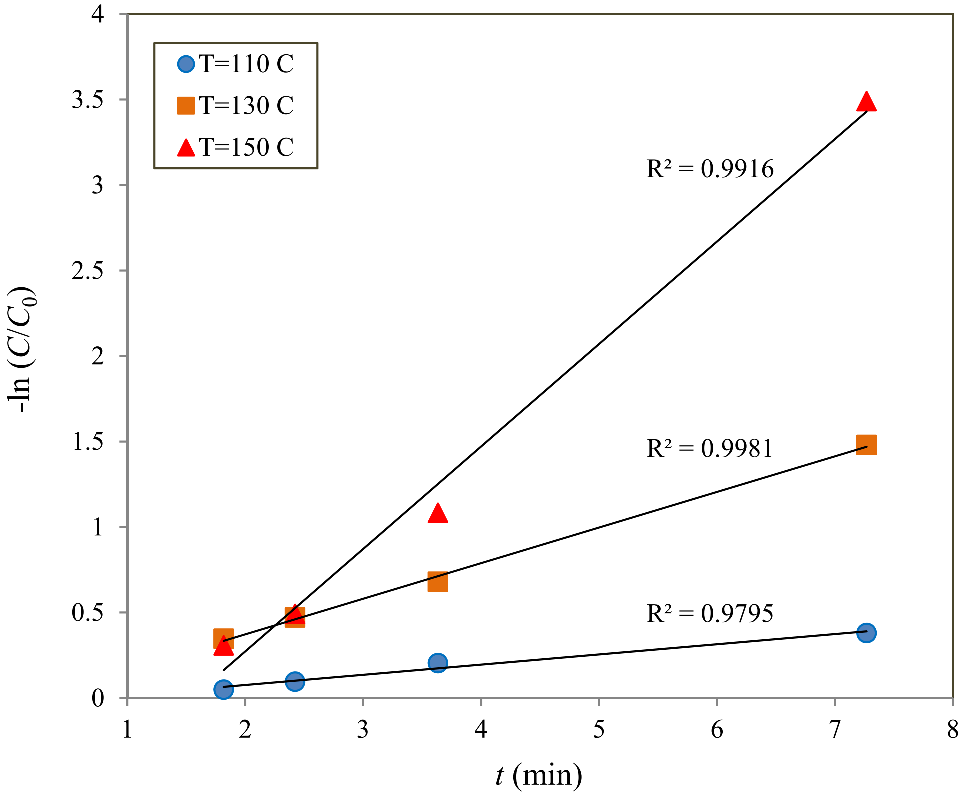

Figure 6.5: First-order kinetics modeling for glucose conversion in the presence of NbP catalyst at different temperatures

The activation energy was also calculated using the temperature dependence of the rate constant (k) expressed by Arrhenius equation as below:

$$k = A \cdot e^{\frac{-E_a}{RT}} \tag{6.12}$$

$$\ln k = \ln A - \frac{E_a}{RT} \tag{6.13}$$

where, k is the reaction rate constant (min^{-1}), E_a is the apparent activation energy of the reaction (J.mol^{-1}), T is the absolute temperature (K), A is the pre-exponential or frequency factor (min^{-1}) and R is the universal gas constant (= 8.314 J.K^{-1}.mol^{-1}). The activation energy and pre-exponential factor were determined by plotting ln (k) versus $1/T$ as shown in Figure 6.6. E_a is obtained from the slope, and A from the intercept of the line with a very good linear trend (linear correlation coefficient R^2 of 0.999). The kinetics parameters (reaction rate constant, apparent activation energy and frequency factor) for glucose conversion in the presence of NbP catalyst are listed in Table 6.4.

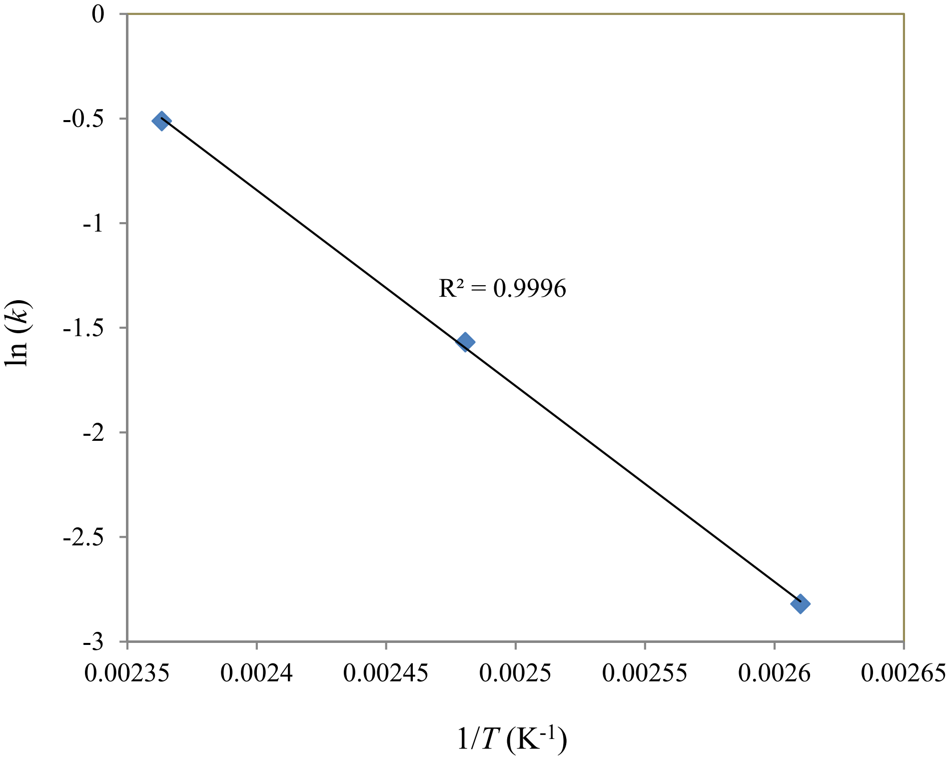

Figure 6.6: Determination of the activation energy from Arrhenius equation for glucose conversion in the presence of NbP catalyst

Table 6.4: Kinetics parameters for glucose conversion in the presence of NbP catalyst

T (°C)	k (min^{-1})	E_a (kJ/mol)	ln A
110	0.0596		
130	0.2083	77.83	21.62
150	0.5993		

It is obvious that by increasing the temperature, the reaction rate constant (*k*) increases, which results in a higher reaction rate at a higher temperature as already observed and discussed. The apparent activation energy (E_a = 77.83 kJ/mol) for overall glucose conversion reaction in the presence of NbP catalyst is in the range of the values reported by Carniti et al. for fructose conversion in the presence of the same catalyst.[23]

6.3.2.5 Stability of the Catalysts with Time

In order to study the stability of the catalysts with time, the experiments with NbP and CrP catalysts and A/O of 1:10 (feeding flow rate of 0.25 ml/min and MIBK flow rate of 2.5 ml/min) were performed and monitored continuously for 24-hour time on stream (TOS) and the results for the activities of the catalysts in terms of glucose conversion and HMF selectivity and yield are shown in Figure 6.7.

The NbP catalyst had almost constant glucose conversion and HMF selectivity and yield for the first 8 hours of time on stream, suggesting stable activities, while the glucose conversion and HMF yield for the CrP catalyst started to decrease continuously from the first hour. Both catalysts showed a considerable drop in glucose conversion and HMF yield after 24 hours, suggesting deactivation of these catalysts after 24 hours TOS, which could be due to the formation of insoluble humins that deposited on the surface of the catalyst particles (as confirmed by the TGA analysis of used catalysts to be discussed in the subsequent section). [23,45] Interestingly, selectivity of both NbP and CrP catalysts remained almost constant during the 24-hour time on stream, although both glucose conversion and HMF yield dropped at a longer TOS.

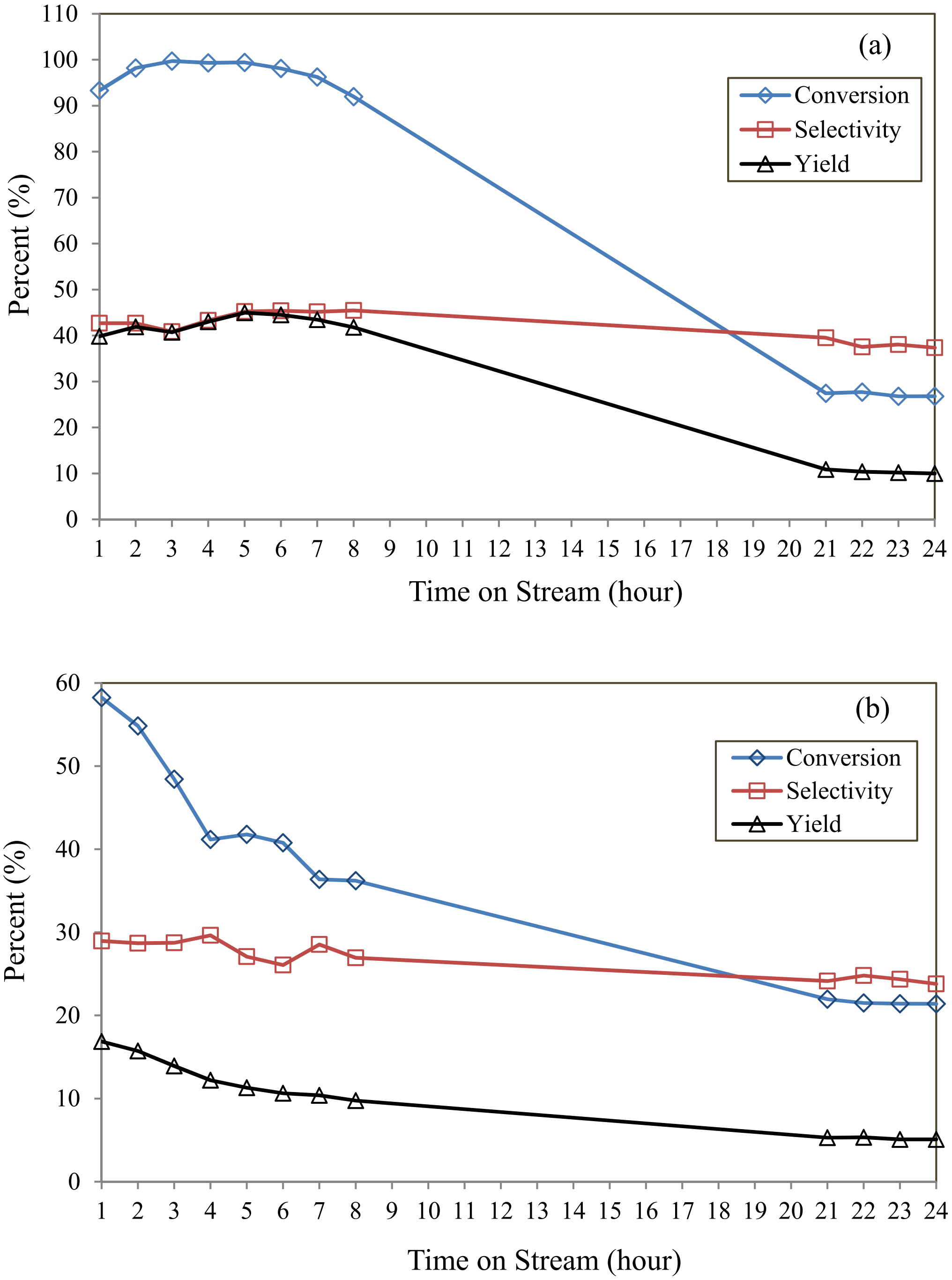

Figure 6.7: Activities of NbP (a) and CrP (b) at 150 °C over the time on stream (Initial glucose concentration of 200 mg/ml, NaCl concentration of 200 mg/ml, Feeding flow rate of 0.25 ml/min, MIBK flow rate of 2.5 ml/min, A/O = 1:10 (v/v))

6.3.3 Characterization of Used Catalysts

To explore the catalyst deactivation mechanism, used NbP catalysts from the experiments at 110 °C, 130 °C and 150 °C after 8-hour time on stream were collected and analyzed by TGA in air to investigate the surface-adsorbed organic species that could lead to deactivation of the catalyst. Figure 6.8 shows the TGA and DTG graphs for the fresh NbP catalyst and the used catalysts after experiment at various temperatures.

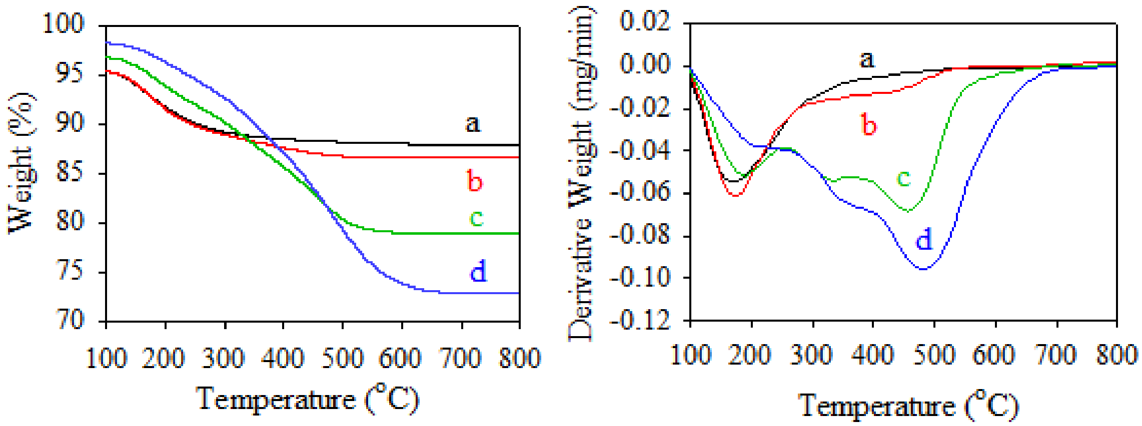

Figure 6.8: TGA/DTG graphs for the fresh NbP catalyst (a) and used NbP catalysts after experiments at 110 °C (b), 130 °C (c) and 150 °C (d)

According to the TGA graphs, the total mass loss between 100-800°C for the fresh NbP catalyst was 7.4% and increased to 8.6%, 17.9% and 25.4% after the 8-hour experiments at 110, 130 and 150 °C, respectively suggesting the deposition of insoluble organic species (humins, heavy oligomers and condensed polymers) on the surface of the catalyst particles during the reaction, leading to catalyst deactivation. Increase in the weight loss of the used catalysts with respect to the reaction temperature indicates that the soluble humins and oligomers formed during the glucose dehydration reaction can convert to insoluble humins and condensed polymers and grow on the catalyst surface as a function of reaction temperature. Similar observations were reported in a literature work on cellobiose dehydration using NbP catalyst at 110-130 °C.[45] The DTG curves of the used catalysts in

Figure 6.8 can be divided into three stages (as shown by three distinct peaks) depending on the rate of weight loss: (1) a peak at 100-250 °C, corresponding to both volatile organic compounds and the coordinated water molecules in the catalyst structure, (2) a shoulder peak at 250-350 °C, corresponding to soft-coke or heavy insoluble oligomers and (3) a main peak at 350-700 °C corresponding to hard-coke or more condensed polymers (in the used catalysts from 130 and 150 °C experiments).[31,32,45]

The used NbP catalysts from the experiments at 110 °C, 130 °C and 150 °C after 8-hour time on stream were also analyzed for BET surface area and pore size distribution (PSD) and the results are presented in table 6.5.

Table 6.5: Textural properties of the fresh NbP catalyst and used NbP catalysts after experiments at 110 °C, 130 °C and 150 °C

Catalyst	BET Surface Area (m^2/g)	Average Pore Diameter (nm)	Total Pore Volume (cm^3/g)
Fresh NbP	246	5	0.31
Used NbP at 110 °C	160	6.2	0.26
Used NbP at 130 °C	118	5.3	0.16
Used NbP at 150 °C	24	4.3	0.03

The results showed that the used NbP catalysts has lower BET surface area and total pore volume compared to the fresh catalyst proving the deposition of insoluble humins on the surface of the catalyst particles during the reaction as a function of reaction temperature. The leaching effect during the reaction could also contribute to the loss of effective surface area and catalyst deactivation mechanism.

6.4 Conclusions

The catalytic dehydration of glucose to HMF was investigated in a biphasic continuous-flow tubular reactor using different solid acids and combination of solid acid and base catalysts. Some major conclusions are summarized below:

- Among the individual catalysts tested for dehydration of glucose to HMF, NbP showed the highest HMF selectivity (38.8%) and yield (37.6%) and close to 100% glucose conversion at 150 ºC, WHSV 0.214 h^{-1} and A/O of 1:5 (v/v). Amb. 36 exhibited the lowest activity in terms of HMF selectivity (21.8%) and yield (6.9%) and CaP found to have the lowest conversion (19.6%). The higher activity of NbP may be attributed to its high acidity (total number of acid sites), presence of both Lewis and Brønsted acid sites on the catalyst surface as well as large BET surface area.

- Mixed solid acid and base catalysts showed very poor activity with respect to HMF selectivity and yield, despite more than 99% glucose conversion obtained, indicating the formation of large amounts of by-products during the reaction. This finding suggest two-step isomerization-dehydration process is likely involved in the conversion of glucose to HMF catalyzed by Lewis acid and Brønsted acid sites, respectively.

- A lower A/O and a higher reaction temperature were found to be in favor of HMF formation. Glucose dehydration in the biphasic continuous-flow tubular reactor with NbP catalyst produced HMF at a very high yield of 45% at 150 ºC and the A/O of 1:10 (MIBK flow rate of 2.5 ml/min and feeding flow rate of 0.25 ml/min) using 200 mg/ml aqueous glucose solution containing 200 mg/ml NaCl as a phase transfer catalyst.

- Kinetics study of the overall glucose conversion reaction in the presence of NbP catalyst showed that a first-order reaction kinetics model adequately fits the experimental data for all three tested temperatures. The reaction rate constants (k) were determined as 0.06, 0.21 and 0.6 min^{-1} at 110, 130 and 150 ºC, respectively, and the apparent activation energy (E_a) was calculated as 77 kJ/mol.

- The activities of NbP and CrP catalysts were found to drop substantially after 24-hour time on stream, suggesting significant deactivation of the catalysts, while the NbP catalyst maintained its activity in the first 8 hours of time on stream.

- Characterization of the used NbP catalyst by TGA/DTG and BET/PSD showed the deposition of insoluble humins on the surface of the catalyst particles during the reaction as a function of reaction temperature, leading to catalysts deactivation.

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Chapter 7

7 HMF Production from Industrial Grade Sugar Syrups Derived from Corn and Wood using Niobium Phosphate Catalyst in a Biphasic Continuous-Flow Tubular Reactor

Abstract

This work demonstrated promise of using industrial grade sugar syrups derived from corn and wood, i.e., high fructose corn syrup (HFCS), glucose corn syrup (GCS) and wood-based sugar (TMP-Bio Sugar), as cheaper and competitive feedstocks for 5-HMF production using niobium phosphate as a heterogeneous solid acid catalyst in a biphasic continuous-flow tubular reactor. HMF yield as high as 53.1% with 100% sugar (glucose and fructose) conversion was obtained from catalytic dehydration of HFCS-90 (containing 90 wt% fructose) at 150 ºC, with feed concentration of 200 mg/ml (glucose and fructose) and aqueous to organic phase ratio of 1:5 (v/v). Catalyst stability with time was tested over 20 hours of continuous time on stream, and the reusability of the catalyst was studied after in-situ regeneration of the used catalyst by calcination in air for removing the deposited humins and coke on the surface of the catalyst particles. The regenerated catalyst showed good activity with almost constant selectivity, although at lower glucose conversion and reduced HMF yield compared to the fresh catalyst, indicating that the in-situ regeneration process could recover a part of the acid sites on the catalyst surface. The produced humins during the reaction were characterized by Fourier transform infrared spectrometry (FT-IR), thermogravimetric analysis (TGA) and elemental analysis (CHNS). The results showed high aromaticity and presence of high degree of unsaturated compounds in the structure of humins.

Keywords: High fructose corn syrup (HFCS), Glucose corn syrup (GCS), TMP-Bio Sugar, 5-HMF, Industrial grade sugar syrups, Biphasic continuous-flow tubular reactor, Niobium phosphate, Catalyst stability, Catalyst regeneration, Humins characterizations

7.1 Introduction

During the past decades with growing concerns on global warming and fossil fuel depletion, intensive attentions have been paid on the development of renewable energies and transformation of biomass resources into chemicals and fuels. A biomass-derived chemical, 5-hydroxymethylfurfural (5-HMF), is a promising versatile and platform chemical leading to a variety of applications in a future bio-refineries.[1] HMF can be converted by straight-forward methods to different useful acids and alcohols for bio-based polymers precursors as well as a promising bio-fuel such as 2,5-dimethylfuran (DMF).[2,3] It can be obtained from acid-catalyzed dehydration of different C_6-based carbohydrates such as glucose, fructose, sucrose and cellulose. Thus in recent years, considerable efforts have been devoted to the transformation of carbohydrates into HMF.[4–13]

High fructose corn syrup (HFCS) is a sweetener made from corn starch and is produced from the isomerization of glucose into fructose at large industrial scale by immobilized enzymes. It has been widely used in the food and beverage industry as an alternative liquid sweetener to sucrose. The use of HFCS was increased from 0.5 lb per capita in 1970 to 62.4 lb per capita in 1997 and remained as high as 59 lb in 2005.[14] Since HFCS is widely available in food industry and is a good source of fructose and glucose, it could be considered as a competitive feedstock for HMF production. Moreover, several studies published in the past 10 years suggested a correlation between the consumption of foods and beverages sweetened by HFCS and obesity, diabetes or other related chronic disease [14–16], which could limit HFCS application as a liquid sweetener in food industry. Thus, using HFCS for production of the platform chemical HMF for bio-fuels and biomass-based materials could create a beneficial and alternative market for the current HFCS producers.

Three classes of HFCS are commonly used in the food industry, namely HFCS-42, HFCS-55 and HFCS-90, containing 42, 55 and 90% (wt% dry basis) fructose, respectively. Corn starch is the initial raw material in the HFCS production process, which is breaked down and converted into glucose via an acid-enzyme process, first forming glucose corn syrup (GCS) after two stages enzymatic hydrolysis using alpha-amylase and glucoamylase enzymes, respectively. The GCS is then treated with an immobilized enzyme (xylose isomerase) to isomerize glucose into fructose with 50–52 wt% glucose and 42 wt% fructose yield with some unconverted oligosaccharides (HFCS-42). The HFCS-42 product could be further processed through liquid chromatography to produce a mixture of 90% fructose and less than 10% glucose (HFCS-90). HFCS-55 is produced by blending HFCS-42 and HFCS-90 at a specific ratio.[1,14,16]

Very little data on the application of HFCS for production of HMF are available in literature. It was recently reported by Jeong et al. that HFCS-90 was used for production of HMF in an organic solvent medium, i.e., 1,4-dioxane, in the presence of Amberlyst-15 as solid acid catalyst in a batch reactor.[1] The effects of various reaction parameters including the amounts of catalyst, initial concentration of HFCS-90, and reaction temperature were studied. The maximum HMF yield was reported to be 80% at 100 ºC and within 3 hours.[1] Interestingly, the authors claimed that the catalyst could be recovered by filtration after the process and reused for up to 5 cycles without a significant loss of its activity. However, too long of a reaction time was found to adversely affect the HMF production due to the formation of by-products such as levulinic acid (LA) and humins.

So far, most research efforts towards HMF production have been made using pure glucose and fructose from food grade and edible carbohydrates; however, using inedible resources such as lignocellulosic biomass as feedstock would be more promising. Lignocellulosic biomass (such as woody biomass) consists of cellulose (~41%), hemicellulose (~28%), and lignin (~27%). Generally, cellulose and hemicellulose can be hydrolyzed to sugars for bioethanol production, and lignin can be employed for production of a variety of aromatic chemicals and transportation fuels.[3] Lignocellulosic biomass is relatively recalcitrant and heterogeneous, making its conversion typically inefficient and uneconomical.[2] Therefore, the development of efficient routes for converting cellulose-derived sugars into 5-HMF is essential for achieving sustainable production of HMF.

In a study by Qi et al. a two-step process for catalytic conversion of cellulose into HMF in ionic liquids at 110 ºC was introduced. In the first step, cellulose was hydrolyzed by gradually adding water in the presence of an acidic cation exchange resin as the catalyst, and as high as 80% glucose yields were reported. In the second step, HMF was produced by using $CrCl_3$ as the homogeneous catalyst with 73% yield.[3] HMF yields of 54% and 24%

have also been reported from cellulosic biomass in organic solvents such as N,N-dimethylacetamide (DMA) containing lithium chloride (LiCl) and ionic liquids as catalysts, respectively.[2,17]

Recently, a technology to convert wood to non-food sugars and lignin has been developed by FPInnovations. The process is patented as thermomechanical pulping-based bio conversion process (TMP-Bio) and involves a pre-treatment of aspen wood chips to produce digestible biomass and hydrolysis of this biomass into TMP-Bio Sugar solution with hydrolysis lignin as a by-product. The produced bio-sugar solution consists of glucose and xylose which are formed from hydrolysis of cellulose and hemicellulose, respectively, as well as some unconverted soluble oligomers from hydrolysis of cellulose, hemicellulose and lignin.

In this work, we aimed to utilize corn and wood-derived industrial grade sugar syrups: TMP-Bio Sugar (non-edible sugar), three types of high fructose corn syrups (HFCS-90, HFCS-55 and HFCS-42) and glucose corn syrup (GCS) as cheaper and competitive feedstocks for HMF production. To the best of our knowledge, no previous studies have been reported on HMF production from all these types of industrial grade sugar syrups, particularly in a biphasic continuous-flow tubular reactor. A commercial niobium phosphate was used as the heterogeneous solid acid catalyst based on our previous studies on the catalytic conversion of fructose and glucose to HMF (Chapters 5 and 6). The sugar conversion, HMF selectivity and yield with different feedstocks were compared. The recyclability and reusability of the used catalyst after regeneration was also tested. The formed humins as the main by-products leading to the deactivation of the catalyst were collected and characterized through elemental analysis (CHNS), Fourier transform infrared spectrometry (FT-IR) and thermogravimetric analysis (TGA). Such data are rarely available in the literature by far.

7.2 Materials and Methods

7.2.1 Materials

Different grades of high fructose corn syrups (HFCS-42, HFCS-55 and HFCS-90) and glucose corn syrup (GCS) samples were supplied by a local plant and their characteristics are listed in Table 7.1. The TMP-Bio Sugar was supplied by FPInnovations, Canada, which contains 320 g/L glucose and 100 g/L xylose. D-(+)-glucose (>99.5%), D-(-)-fructose (>99%) and 5-hydroxymethylfurfural (99%) for preparing HPLC standard solutions as well as sodium chloride (NaCl) and triethylamine (TEA) were purchased from Sigma-Aldrich. Niobium phosphate hydrate ($NbOPO_4.nH_2O$) was supplied by CBMM (Companhia Brasileira de Metalurgia e Mineraçã). HPLC grade water and acetonitrile for preparing the mobile phase for HPLC analysis as well as methyl isobutyl ketone (MIBK) were purchased from Caledon Laboratory Chemicals, and used as received.

Table 7.1: Characteristics of the HFCS and GCS samples

Sample	Dry Substance (wt%)	Fructose (wt% db [a])	Glucose (wt% db [a])	Higher Saccharides (wt% db [a])
HFCS-42	70.5-71.5	42.0	52.0	6.0
HFCS-55	76.8-77.4	55.0	40.0	5.0
HFCS-90	77.4	92.1	5.6	2.3
GCS	48.0	3.2	91.4	5.4

[a] Dry Basis

7.2.2 Catalyst Preparation

In order to be able to use powder solid catalysts as a fixed-bed of catalysts in a plug flow reactor, pelletization of the powder catalyst was performed. In brief, niobium phosphate (thereafter named as NbP) powder was first humidified overnight and then was pressed in a pellet die using a hydraulic press at 10 tonnes/cm^2 of pressure to create self-supported disks. The disks were then crushed using a Wiley Mill and sieved to particle sizes between 420-840 μm (Mesh No. 40 to Mesh No. 20) for the experiments.

7.2.3 Continuous-Flow Reactor Setup and Experimental Procedure

The catalytic conversion of corn and wood derived sugars (HFCSs, GCS and TMP-Bio Sugar) to HMF was performed in a novel biphasic continuous-flow tubular reactor designed and constructed in-house by the authors. The schematic diagram and detailed description of this lab-scale tubular reactor setup as well as the experimental procedure have been presented previously in Chapter 5. For the experiments in this chapter, diluted HFCSs, GCS and TMP-Bio Sugar samples in aqueous medium was used as the feedstock and MIBK was utilized as the extracting organic solvent. MIBK continuously extracts the produced HMF from the aqueous medium in-situ inside the fixed-bed catalytic reactor in order to enhance the HMF selectivity and yield by suppressing the side reactions of HMF in water. Sodium chloride (NaCl) was also added to the aqueous phase of feedstock as the phase transfer catalyst (PTC) to enhance the partition coefficient of HMF towards organic phase (via the salting-out effect).

The time on stream (TOS) for all of the experiments was 4 hours, except for an experiment with GCS which were continued for 20 hours to examine the catalyst stability. and no detectable soluble by-product or any other intermediate was found in the HPLC chromatographs.

7.2.4 Product Analyses

Each phase (organic and aqueous) of the product samples collected from the experiments was separately analyzed using an HPLC system to determine the amount of feedstock (glucose and fructose) consumed and the amount of product (HMF) produced and the results were calculated and reported in terms of sugar conversion, HMF selectivity and yield. The detailed description of the HPLC system and analysis procedure as well as the definitions of conversion, selectivity and yield have been presented in our previous work (Chapter 5 and 6). In the present work we used the sum total of glucose and fructose moles (concentrations) as the basis for calculation of the conversion, selectivity and yield.

7.2.5 By-Products Characterization Methods

To characterize humins as the main by-products from the sugar dehydration reactions, the insoluble humins were collected after the experiment with HFCS-90 as the feedstock. After the experiment, the catalyst bed inside the tubular reactor was rinsed by pumping a mixture of isopropanol and ethanol (50:50 v/v) and distilled water consecutively, and then the reactor was opened and the deposited humins on the inner wall of the tubular reactor outlet were collected and dried at 105 °C for analyses.

Elemental analysis (CHNS) was performed on a Flash EA 1112 analyzer, employing 2,5-Bis (5-tert-butyl-benzoxazol-2-yl) thiophene (BBOT) as the calibration standard. The composition of oxygen was calculated by difference.

Fourier transform infrared spectrometer (FT-IR) analysis was conducted on a PerkinElmer FT-IR spectrometer and the spectra were recorded in the region of 4000-550 cm^{-1}.

Thermogravimetric analysis (TGA), volatile matter (VM) and fixed carbon (FC) contents were performed and determined using a PerkinElmer Pyris 1 TGA in nitrogen or air atmosphere with the gas flow rate of 20 ml/min. Briefly, the sample was first heated under nitrogen flow from 40 °C to 800 °C at 10 °C/min and the change in the sample weight against temperature was recorded. The gas flow was then switched to air with the same flow rate and the samples were burned in the air at 800 °C for 10 minutes to determine their fixed carbon (FC) and ash content. Derivative thermogravimetric (DTG) graph was obtained from first derivative of TGA results with respect to time or temperature.

7.3 Results and Discussion

7.3.1 Catalytic Production of HMF from Different Industrial Grade Sugar Syrups Derived from Corn and Wood

Different grades of HFCSs as well as GCS and TMP-Bio Sugar samples were used as feedstocks for production of HMF in a continuous-flow tubular reactor. The experiments were performed in the presence of niobium phosphate as the best solid acid catalyst (the comprehensive characterization of this catalyst was already presented and discussed) and at the best operating conditions found in our previous studies (Chapter 5 and 6) for dehydration of fructose and glucose to HMF: reaction temperature of 150 °C, substrate and NaCl concentration (in aqueous feedstock solution) both at 200 mg/ml, aqueous to organic phase ratio of 1:5 (v/v) (feeding flow rate of 0.25 ml/min and MIBK flow rate of 1.25 ml/min) and catalyst loading of 14 g (WHSV = 0.214 hr^{-1}). The HFCS, GCS and TMP-Bio Sugar samples were diluted with deionized water so that the sum total concentration of glucose plus fructose in all of the aqueous feedstock solutions was adjusted to 200 mg/ml. The results of the experiments are presented in Table 7.2.

Table 7.2: HMF production from different industrial grade sugar syrups derived from corn and wood in the presence of NbP catalyst at 150 °C [a]

Feedstock	Conversion (%)	Selectivity (%)	HMF Yield (%)		
			Aqueous Phase	Organic Phase	Total
HFCS-90	100	53.0 ± 2.2	4.8 ± 1.0	48.3 ± 0.2	53.0 ± 1.2
HFCS-55	99.5 ± 0.1	50.3 ± 0.9	4.6 ± 0.7	45.5 ± 0.3	50.0 ± 0.8
HFCS-42	98.7 ± 0.3	47.7 ± 1.4	4.4 ± 0.8	42.7 ± 0.2	47.1 ± 1.1
GCS	96.9 ± 0.8	40.4 ± 1.3	3.7 ± 0.5	35.4 ± 0.6	39.1 ± 1.1
TMP-Bio Sugar	62.8 ± 2.4	33.8 ± 1.1	2.3 ± 0.4	19.0 ± 1.8	21.3 ± 2.2

[a] Initial glucose + fructose concentration of 200 mg/ml (~20 wt%), NaCl concentration of 200 mg/ml, Feeding flow rate of 0.25 ml/min, MIBK flow rate of 1.25 ml/min, A/O of 1:5 (v/v), Catalyst loading of 14 g

As shown in the Table, in all experiments the isolated HMF yield in the organic phase was found to be considerably higher than that in the aqueous phase, indicating very efficient extraction of HMF by MIBK into the organic phase. Using HFCS feedstocks resulted in a relatively higher HMF yield, with almost complete sugar conversion. The HMF selectivity and yield from these feedstocks varied according to their fructose content. It is widely known that HMF could be produced more readily through the acid-catalyzed dehydration of fructose than glucose with higher yields.[8,18] Since the HFCS-90 feedstock contains the highest fructose content among all other sugar feedstocks tested, the highest HMF yield (53%) was obtained with the HFCS-90, as expected. The TMP-Bio Sugar and GCS samples were mostly composed of glucose, so their HMF yields were both lower than those from the HFCS feedstocks. It was observed that the xylose content of TMP-Bio Sugar was also dehydrated and converted into furfural, confirmed by HPLC analysis of both aqueous and organic phases of the product from the TMP-Bio Sugar, although the furfural yield was not quantitatively determined in this study. Despite the fact that both GCS and TMP-Bio Sugar samples were diluted to have the equal concentration of glucose (200 mg/ml), the lower glucose conversion and HMF yields from the TMP-Bio Sugar compared to those from the GCS is likely due to the presence of impurities in the TMP-Bio Sugar which could deactivate the catalyst by masking the active sites on the catalyst surface during the experiments. The impurities in the TMP-Bio Sugar feedstock mostly consist of soluble polymers and oligomers formed as a result of hydrolysis of cellulose, hemicellulose and lignin. Thus, some pre-treatment and purification processes (e.g., adsorption, filtration and membrane separation) is recommended to better utilize TMP-Bio Sugar as an inedible feedstock for HMF production.

7.3.2 Stability of the NbP Catalyst with Time on Stream and Reusability of the Used Catalyst

In order to study the stability of the NbP catalyst, the experiment with the GCS feedstock was continued and monitored for 20 hours of continuous time on stream, and the feedstock conversion and HMF selectivity and yield are shown in Figure 7.1.

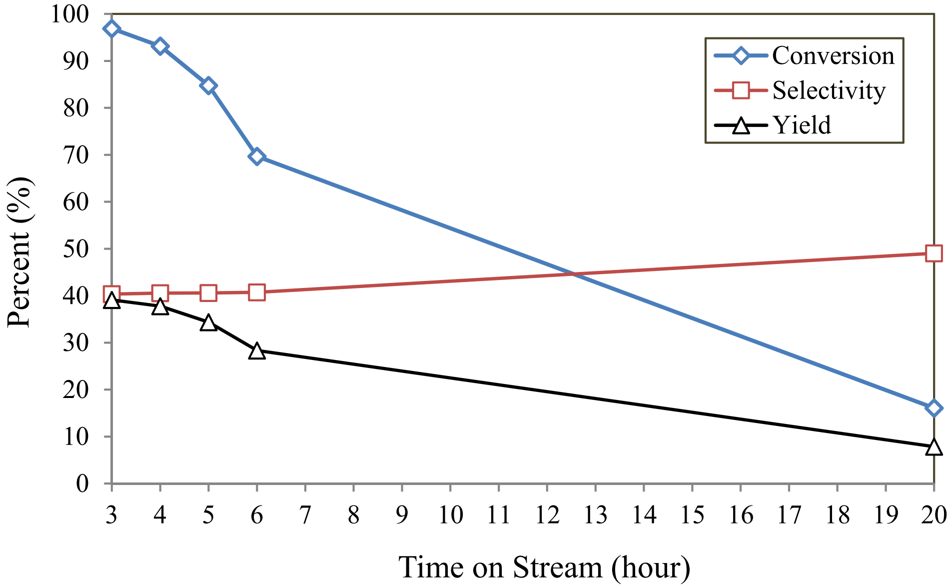

Figure 7.1: Activity of NbP catalyst over time on stream for conversion of GCS to HMF at 150 °C (Initial glucose + fructose concentration of 200 mg/ml, NaCl concentration of 200 mg/ml, Feeding flow rate of 0.25 ml/min, MIBK flow rate of 1.25 ml/min, A/O of 1:5 (v/v), Catalyst loading of 14 g (WHSV = 0.214 h^{-1}))

While the HMF selectivity remained almost constant at around 40.5%, glucose conversion was decreased from 96.9% to 69.7% in the first 6 hours TOS. Consequently, HMF yield decreased from 40% to less than 30% after 6 hours TOS. In the subsequent 14 hours TOS, the HMF selectivity increased to 50%, but there was a considerable drop in glucose conversion, resulting in a substantial decrease in HMF yield, suggesting catalyst deactivation likely due to the deposition of insoluble humins on the catalyst surface.[19,20]

Reusability of the used catalyst was examined by regeneration of the used catalyst through in-situ calcination in air flow. The used catalysts from the experiment after 20 hours TOS as described above was rinsed by pumping mixed solvent of isopropanol and ethanol (50:50 v/v), and distilled water through the reactor, consecutively. The tubular reactor was then placed inside an oven at 105 °C overnight (without removing the used catalyst) for drying the catalyst bed, followed by calcination in-situ inside a tubular furnace at 600 °C (heating rate of 10 °C/min) for 4 hours and 100 ml/min air flow through the tubular reactor (catalyst bed). After cooling, the regenerated catalyst was used again in a new experiment with the same operating conditions as described in the previous experiment for the conversion of GCS feedstock to HMF. The activities of the fresh NbP catalyst (at 3 hours TOS), fresh catalyst (after 20 hours TOS) and the regenerated catalyst (at 3 hours TOS) for conversion of GCS to HMF are compared in Table 7.3.

Table 7.3: Comparison of activities for fresh NbP catalyst (at 3 hours TOS), fresh NbP catalyst (after 20 hours TOS) and regenerated NbP catalyst (at 3 hours TOS) for conversion of GCS to HMF at 150 °C [a]

NbP catalyst	Conversion (%)	Selectivity (%)	HMF Yield (%)		
			Aqueous Phase	Organic Phase	Total
Fresh (at 3 hr TOS)	96.9 ± 0.8	40.4 ± 1.3	3.7 ± 0.5	35.4 ± 0.6	39.1 ± 1.1
Fresh (after 20 hr TOS)	16.1	49.0	0.7	7.2	7.9
Regenerated (at 3 hr TOS)	75.3 ± 2.0	36.7 ± 1.8	2.7 ± 1.2	25.0 ± 0.7	27.7 ± 1.9

[a] Initial feedstock (glucose) concentration of 200 mg/ml (~20 wt%), NaCl concentration of 200 mg/ml, Feeding flow rate of 0.25 ml/min, MIBK flow rate of 1.25 ml/min, A/O of 1:5 (v/v), Catalyst loading of 14 g, (WHSV = 0.214 h^{-1})

The regenerated catalyst showed partially recovered activity, with almost the same selectivity (40%), and >75% glucose conversion and around 30% HMF yield, although still lower than those of the fresh NbP catalyst. Thus, the used catalyst could be reactivated in-situ and reused without losing much of its activity. This also proves that the in-situ calcination of the used catalyst in air can effectively burn the insoluble humins and cokes deposited on the catalyst surface and regenerate the available acid sites of the catalyst for the further usage. On the other hand, the regeneration process did not completely recover the activity of the used catalyst to the same level of the fresh catalyst. This implies that although the deposition of the insoluble humins on the surface of the catalyst is the main cause of catalyst deactivation, other mechanisms such as loss of catalyst surface area and acidity of the catalyst in the reaction process (leaching effects) might also partially contribute to the catalyst deactivation.[20,21]

7.3.3 Characterization of the Humins By-product

As discussed above, deposition of the insoluble humins on the surface of the catalyst is likely the main cause of catalyst deactivation, responsible for the loss of active sites on the surface of the catalyst after a long time on stream. In order to have a better understanding of the nature and structure of the insoluble humins, the humin by-product was collected and characterized in this work by elemental analysis (CHNS), FT-IR and TGA/DTG.

The results of elemental analysis of the humin sample are presented in Table 7.4 on a moisture-free basis.

Table 7.4: Elemental composition of the humins by-product compared with glucose/fructose and HMF

	Elemental Composition (wt%)			Molar Ratio	
Sample	C	H	O[a]	H/C	O/C
Humin	59.87	5.09	34.17	1.02	0.43
Glucose/Fructose	40.00	6.67	53.33	2	1
HMF	57.14	4.77	38.09	1	0.5

[a] By Difference

The elemental compositions of glucose/fructose and HMF are also calculated from their chemical formula and listed for comparison. The carbon content of the humin sample (~60%) was considerably higher than that of the glucose and fructose as substrates (40%), while the oxygen content was much lower. The elemental composition of humins collected in this work was very close to that of HMF, and similar to the results presented by Rasrendra et al.[22]

The Van Krevelen diagram for humins, glucose/fructose and 5-HMF is presented in Figure 7.2, where the molar H/C and O/C ratios of various compounds are displayed. The dehydration line of glucose/fructose is also shown on this diagram. Both humin by-product and HMF product have considerably lower oxygen and hydrogen contents than the starting materials (glucose/fructose), and their H/C and O/C molar ratios are very close to each other and well align with the sugar dehydration line. This indicates that the insoluble humins are produced from either dehydration of glucose/fructose or self-polymerization of HMF (without further dehydration). The similarity of chemical structure of humin to that of HMF could also be observed in the FT-IR spectrum (Figure 7.3) by the existence of the vibrations attributed to furan rings in the structure of humins. A lower H/C value for humins compared with that of the sugars also suggests a higher degree of unsaturated bonds and aromatic nature in the molecular structure of humins [23], as evidenced in FT-IR spectrum.

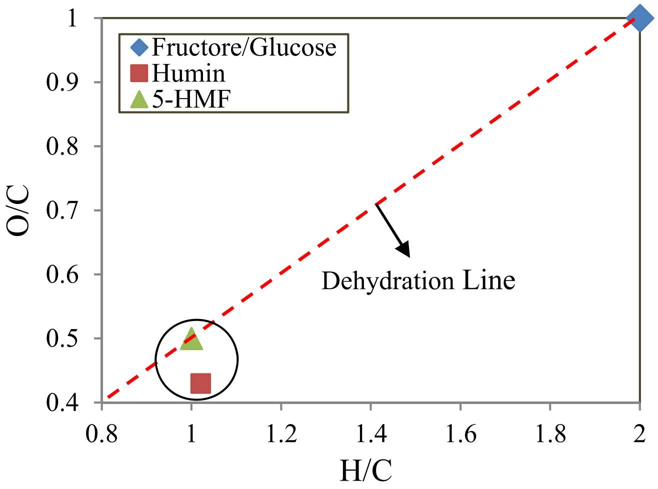

Figure 7.2: Van Krevelen diagram for humins, glucose/fructose and HMF

The FT-IR spectrum of the humins by-product is shown in Figure 7.3. The broad absorption at 3400 cm^{-1} is typical of O-H stretching of hydroxyl groups. The band at 2920 cm^{-1} represents the saturated C-H stretching vibrations indicating the presence of alkyl C-H groups. The absorbance at 1700 cm^{-1} represents the C=O stretching vibrations. The peaks at 1213 cm^{-1} and 1026 cm^{-1} represent the C-O and O-H stretching vibrations of COOH and the C-O vibrations of polysaccharides or Si-O of silicate impurities (from the quartz wool plugs inside the reactor to support the catalyst bed), respectively. The three peaks at 1700, 1213 and 1026 cm^{-1} are indicative of existence of oxygen functionalities such as ethers, aldehydes/ketones that are incorporated in the humins structure. The existence of furan rings in the humin structure is evident from the presence of C=C stretching bands at 1615 cm^{-1} and 1516 cm^{-1}, C-O stretching band at 1370 cm^{-1} and C-H out-of-plane deformation signals at 850–700 cm^{-1}. The bands at 1700, 1615 and 1213 cm^{-1} are the common characteristic IR absorption bands of humic materials.[22–25]

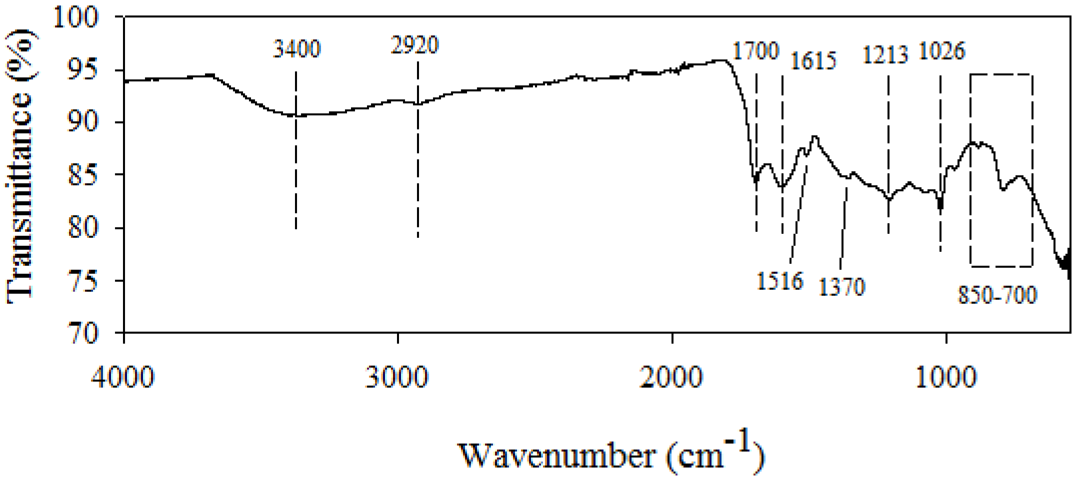

Figure 7.3: FT-IR spectrum of the humin by-product

The humin by-product was further characterized by TGA in nitrogen atmosphere, and the results are shown in Figure 7.4. A similar thermal degradation behavior of humins was observed by Rasrendra et al.[22] The small weight loss observed at <100 ºC is due to the volatilization of some residual water or volatile organic compounds. The thermal decomposition of the humin sample in nitrogen atmosphere starts at 265 ºC and levels off at around 700 ºC. The total mass loss of the sample was 52.6 wt%, representing the volatile matter (VM) content of the humin by-product. The fixed carbon (FC) and ash content were further measured to be 46.5 wt% and 0.87 wt%, respectively, by switching the atmosphere from nitrogen to air at 800 ºC for 10 min to burn the carbon residue. According to the DTG graph, the major thermal degradation peak temperature for the humin by-product was observed at around 350 ºC.

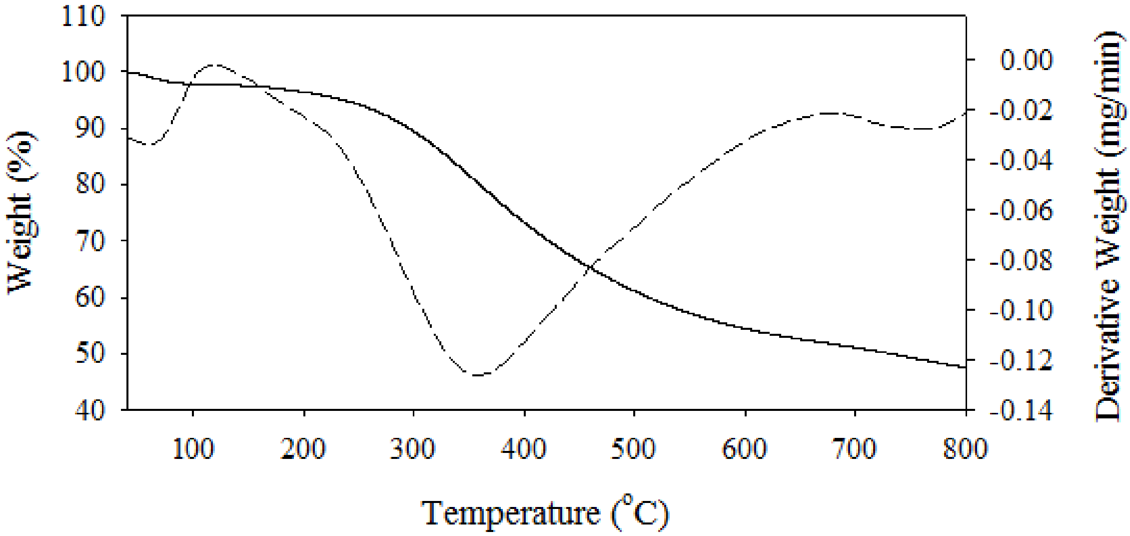

Figure 7.4: TGA/DTG graphs for the humins by-product

7.4 Conclusions

This work demonstrated promise of conversion of corn and wood-derived industrial grade sugar syrups into 5-HMF in a biphasic continuous-flow tubular reactor using heterogeneous NbP catalyst at 150 °C.

- Catalytic dehydration of different grades of high fructose corn syrup (HFCSs) and glucose corn syrup (GCS) feedstocks in the presence of NbP catalyst resulted in high HMF yield and complete sugar conversion. The HMF selectivity and yield from these feedstocks varied according to their fructose content and the highest HMF yield of 53.1% was obtained with HFCS-90 (containing 90 wt% fructose).

- The TMP-Bio Sugar (wood-based sugar) and glucose corn syrup (GCS) feedstocks were mostly composed of glucose, so their HMF yields were much lower than those of HFCS feedstocks, being 21.3% and 39.1%, respectively. The lower glucose conversion and HMF yield from the TMP-Bio Sugar compared to GCS was likely due to the presence of impurities such as soluble polymers and oligomers produced from hydrolysis of cellulose, hemicellulose and lignin. Therefore, some pre-treatment and purification processes (e.g., adsorption, filtration and membrane separation) is recommended to better utilize TMP-Bio Sugar as an inedible feedstock for HMF production.

- The NbP catalyst after 20-hour time on stream for the GCS dehydration experiment resulted in a considerable drop in glucose conversion, and a substantial decrease in HMF yield, suggesting catalyst deactivation likely due to deposition of insoluble humins on the surface of the catalyst particles.

- The regenerated catalyst by in-situ calcination showed partially recovered activity, with almost the same selectivity (40%), and >75% glucose conversion and around 30% HMF yield, although still lower than those of the fresh NbP catalyst, which implied that the deposition of the insoluble humins on the surface of the catalyst is the main cause of catalyst deactivation.

- Characterizations of the insoluble humin by-product collected in this work showed that the humins had similar elemental composition to that of HMF. It was further confirmed in this work that the insoluble humins were produced from either dehydration of glucose/fructose or self-polymerization of HMF (without further dehydration). The chemical structure of humins was similar to that of HMF, containing furan and unsaturated structure.

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Chapter 8

8 Conclusions, Contributions and Recommendations

8.1 General Conclusions

The aim of this study was to develop a cost-effective continuous-flow process for production of HMF from simple sugars (particularly glucose and fructose) and industrial grade sugar syrups in a biphasic (aqueous/organic) media using inexpensive heterogeneous catalyst. Catalytic experiments were performed in a novel biphasic continuous-flow tubular reactor, devised and constructed in-house by the authors. Commercial and synthesized heterogeneous acid and base solid catalysts were used for the catalytic experiments and their activities in the terms of conversion, selectivity and yield were compared. Considering and assuming the proposed two-step reaction pathway theory for the catalytic conversion of glucose to HMF, the experimental approach for this research was to conduct this process in two separate steps: First glucose isomerization to fructose using heterogeneous solid base catalysts and then fructose dehydration to HMF using heterogeneous solid acid catalysts. Thereafter, continuous single-step conversion of glucose and industrial grade sugar syrups derived from corn and wood to HMF was investigated. In each section, fresh catalysts were characterized comprehensively and the stability and feasibility of recycling and reusing of some selected catalysts were examined. The effects of different experimental conditions including reaction temperature, feeding flow rate, initial feedstock concentration, catalyst loading, presence of extracting organic solvent and phase transfer catalyst were also studied. The deactivation mechanism of the catalysts was investigated by analysing the used catalysts and the insoluble humins produced during the reaction as the main by-product responsible for the catalyst deactivation.

The following detailed conclusions could be drawn from the individual experimental chapters (Chapters 3-7) of this research:

1) Characterization of the solid base catalysts by XRD, TGA and FT-IR confirmed the hydrotalcite structure for the HT-C-R, HT MG30 and HT MG30/K_2CO_3 catalysts.

However, according to XRD data, HT-C-R had more uniform and bigger crystals. The two commercial hydrotalcite catalysts exhibited much larger BET surface areas compared to HT-C-R. MgO was found to have the smallest BET surface area among all other catalysts tested suggesting a nonporous structure. Amberlyst A21 had the most diverse functional groups compared to other catalysts based on FT-IR analyses. MgO was the most active catalyst for glucose isomerization reaction with the glucose conversion of 62.7% and the fructose yield of 25.1% at 120 ºC. However, the highest fructose selectivity (78.1%) was obtained by HT-C-R at 100 ºC. This catalyst had the highest fructose yield of 19.5% at 120 ºC after MgO. Despite the large BET surface area of the commercial hydrotalcite catalysts, they did not show a superior activity in glucose isomerization reaction, suggesting that the BET surface area could not be considered as a key indicator of the catalyst activity for this reaction. Increasing the reaction temperature from 80 ºC to 120 ºC led to increased glucose conversion and fructose yield in the presence of MgO and HT-C-R catalysts. However, the selectivity of these catalysts decreased with increasing temperature, and the drop in selectivity was greater for MgO compared to HT-C-R. Stability test for MgO and HT-C-R over 4 hours of continuous time on stream showed a little drop in glucose conversion and almost constant fructose yield suggesting that these catalysts are effective for glucose isomerization reaction in a continuous-flow reactor with a good stability. Calcination temperature of 450 ºC was found to be more effective than 350 ºC to improve the catalytic activity and performance of hydrotalcite catalyst for glucose isomerization reaction.

2) Characterization of the hydrotalcite catalysts confirmed the double layered structure and the memory effects of hydrotalcite through the calcination and rehydration process. It was also revealed that after rehydration of calcined hydrotalcite, carbonate anions are significantly substituted by water molecules in the layered structure. From all of the results, it appears that hydrotalcite was an effective catalyst for isomerization of glucose to fructose in a continuous-flow reactor with good glucose conversion, fructose selectivity and yield. The maximum fructose yield in the presence of activated hydrotalcite catalyst was 18.7% at 130 ºC (48.8% glucose conversion and 38.3% fructose selectivity) with feeding flow rate of 0.5 ml/min and 2 g catalyst loading, which

is considerably higher than the uncatalyzed (blank) reaction (0.3-0.6%). Higher temperature as well as more catalyst loading and lower feeding flow rate (longer retention time) were found to be favorable for higher glucose conversion but had detrimental effects on fructose selectivity. The untreated used HT-C-R catalyst showed lower glucose conversion and higher fructose selectivity compared to the fresh catalyst without significant loss in fructose yield. However, the regenerated used catalyst exhibited almost the same performance as the fresh catalyst in terms of conversion, selectivity and yield. Suggesting that the activity of the used catalyst can be restored through calcinations-rehydration process.

3) It was demonstrated that HMF selectivity and yield from fructose were significantly higher in biphasic system than in a single aqueous phase. With the biphasic media, increasing the extracting organic solvent to aqueous phase ratio (or decreasing A/O), employing a phase transfer catalyst (NaCl) and using more concentrated feedstock had positive effects on fructose dehydration reaction, leading to significantly increased HMF selectivity and yield. At lower reaction temperatures (110 and 130 ºC), NbP and NbP-syn showed considerably higher activities than other catalysts tested, attributed to their larger total number of acid sites, higher Brønsted to Lewis acid sites ratio (B/L) and larger BET surface area. The activity of the catalysts improved with increasing temperature and this enhancement was surprisingly drastic for Amb. 36. With Amb. 36 while increasing the temperature from 110 ºC to 150 ºC, the fructose conversion increased from 30.3% to 77.5%, and HMF selectivity jumped from <6% to 70.1%. NbP, NbS-syn and Amb. 36 were the most active catalysts among all catalysts tested for dehydration of fructose to HMF. The best operating conditions for catalytic dehydration of fructose to HMF in the continuous-flow reactor are: temperature of 150 ºC, aqueous feed flow rate of 0.25 ml/min, organic (MIBK) flow rate of1.25 ml/min, fructose and NaCl concentrations in the aqueous feedstock solution of 200 or 400 mg/ml and 200 mg/ml, respectively. With these three catalysts (NbP, NbS-syn and Amb. 36) at the best operating conditions, fructose dehydration in the biphasic continuous-flow tubular reactor produced HMF at both high selectivity (55-70%) and high yield (54-60%). The Amb. 36 catalyst showed a superb stability after 8 hours of time on stream, with even better selectivity and only a small decrease in fructose conversion and HMF yield.

Therefore, Amb. 36 is expected to have a longer lifetime in real applications. The catalyst deactivation mechanisms were investigated by TGA analysis of the used NbP catalyst at different reaction temperatures, and the results evidenced that the deposition of insoluble humins on the surface of the catalyst particles is one of the main mechanisms for catalyst deactivation.

4) Among the individual catalysts tested for dehydration of glucose to HMF, NbP showed the highest HMF selectivity (38.8%) and yield (37.6%) and close to 100% glucose conversion at 150 ^{o}C, WHSV 0.214 h^{-1} and A/O of 1:5 (v/v). Amb. 36 exhibited the lowest activity in terms of HMF selectivity (21.8%) and yield (6.9%) and CaP found to have the lowest conversion (19.6%). The higher activity of NbP may be attributed to its high acidity (total acid sites), presence of both Lewis and Brønsted acid sites on the catalyst surface as well as large BET surface area. Mixed solid acid and base catalysts showed very poor activity with respect to HMF selectivity and yield, despite more than 99% glucose conversion obtained, indicating the formation of large amounts of by-products during the reaction. This finding suggest two-step isomerization-dehydration process is likely involved in the conversion of glucose to HMF catalyzed by Lewis acid and Brønsted acid sites, respectively. A lower A/O and a higher reaction temperature were found to be favourable to HMF formation. Glucose dehydration in the biphasic continuous-flow tubular reactor with NbP catalyst produced HMF at a very high yield of 45% at 150 ^{o}C and the A/O of 1:10 (MIBK flow rate of 2.5 ml/min and feeding flow rate of 0.25 ml/min) using 200 mg/ml aqueous glucose solution containing 200 mg/ml NaCl as a phase transfer catalyst. Kinetics study of the overall glucose conversion reaction in the presence of NbP catalyst showed that a first-order reaction kinetics model adequately fits the experimental data for all three tested temperatures. The reaction rate constants (k) were determined as 0.06, 0.21 and 0.6 min^{-1} at 110, 130 and 150 ^{o}C, respectively, and the apparent activation energy (E_a) was calculated as 77 KJ/mol. The activities of NbP and CrP catalysts were found to drop substantially after 24-hour time on stream, suggesting significant deactivation of the catalysts, while the NbP catalyst maintained its activity in the first 8 hours of time on stream. Characterization of the used NbP catalyst by TGA/DTG and BET/PSD showed the deposition of insoluble humins on the surface of the catalyst particles during the reaction as a function of reaction

temperature, leading to catalysts deactivation.

5) Catalytic dehydration of different grades of high fructose corn syrup (HFCSs) and glucose corn syrup (GCS) feedstocks in the presence of NbP catalyst resulted in high HMF yield and complete sugar conversion. The HMF selectivity and yield from these feedstocks varied according to their fructose content and the highest HMF yield of 53.1% was obtained with HFCS-90 (containing 90 wt% fructose). The TMP-Bio Sugar (wood-based sugar) and glucose corn syrup (GCS) feedstocks are mostly composed of glucose, so their HMF yields are much lower than those from the HFCS feedstocks, being 21.3% and 39.1%, respectively. The lower glucose conversion and HMF yield from the TMP-Bio Sugar compared to GCS was likely due to the presence of impurities such as soluble polymers and oligomers produced from hydrolysis of cellulose, hemicellulose and lignin. Therefore, some pre-treatment and purification processes (e.g., adsorption, filtration and membrane separation) is recommended to better utilize TMP-Bio Sugar as an inedible feedstock for HMF production. The NbP catalyst after 20-hour time on stream for the GCS dehydration experiment resulted in a considerable drop in glucose conversion, and a substantial decrease in HMF yield, suggesting catalyst deactivation likely due to deposition of insoluble humins on the surface of the catalyst particles. The regenerated catalyst by in-situ calcination showed partially recovered activity, with almost the same selectivity (40%), and >75% glucose conversion and around 30% HMF yield, although still lower than those of the fresh NbP catalyst, which implies that the deposition of the insoluble humins on the surface of the catalyst is the main cause of catalyst deactivation. Characterizations of the insoluble humin by-product collected in this work showed that the humins had similar elemental composition to that of HMF. It was further confirmed in this work that the insoluble humins were produced from either dehydration of glucose/fructose or self-polymerization of HMF (without further dehydration). The chemical structure of humins was similar to that of HMF, containing furan and unsaturated structure.

8.2 Major Contributions

The newly invented process for HMF production possess a “combination” of several significant features and advantages which have not been utilized altogether in the existing and reported processes, including:

1) Using biphasic continuous-flow tubular reactor
2) Using inexpensive and effective mineral and commercial solid catalysts
3) Using aqueous medium as an inexpensive and green solvent
4) Using an inexpensive inorganic salt (NaCl) as a phase transfer catalyst
5) Using an immiscible organic solvent (MIBK) as an extracting agent
6) Using corn and wood-derived sugar syrups with high HMF selectivity and yield
7) Having great potential for upscaling to industrial and commercial scale

8.3 Recommendations for Future Works

1) The catalytic conversion of fructose, glucose and industrial grade sugar syrups to HMF in a novel biphasic continuous-flow tubular reactor using low cost heterogeneous solid catalysts resulted in very good HMF yields compared to similar works reported in batch reactors using expensive synthetic catalysts and solvents. However, more research works needs to be done to enhance the product yield in a continuous reactor.

2) Although various operating conditions was tested to achieve the best product yield, it would be interesting to see if optimization of process conditions by statistical design of experiments methods could further increase the final yield of product.

3) More investigation and study on the mechanism of the reactions as well as formation kinetics of the final product, by-products and intermediates is highly recommended.

4) Despite the promising results obtained for conversion of pure and industrial grade sugar syrups to HMF, efficient continuous processes for single-step conversion of cellulosic biomass to HMF should also be investigated.

5) Conversion of HMF as an intermediate and platform chemical to the valuable final products (fuels and chemicals) in a continuous-flow reactor needs more research work.

6) Although commercial solid catalyst tested in this study showed acceptable performance in isomerization of glucose to fructose and dehydration of fructose/glucose to HMF, more research is needed to explore the possibility of modifying these catalysts to enhance their activity and selectivity toward the final product.

7) Detail investigation and study on the structure and nature of humins and other by-products and intermediates is of great importance in order to have a better understanding of the reactions pathway and mechanism.

8) Different extracting organic solvents should be tested to find the most effective organic solvent with optimum ratio for the maximum HMF production.

9) Extensive research work for catalytic isomerization of glucose to fructose is still needed to select an efficient catalyst and best operating conditions to compete with industrial enzymatic process.

10) Detailed energy consumption calculations as well as technoeconomical analysis of the whole process should be investigated before its commercialization

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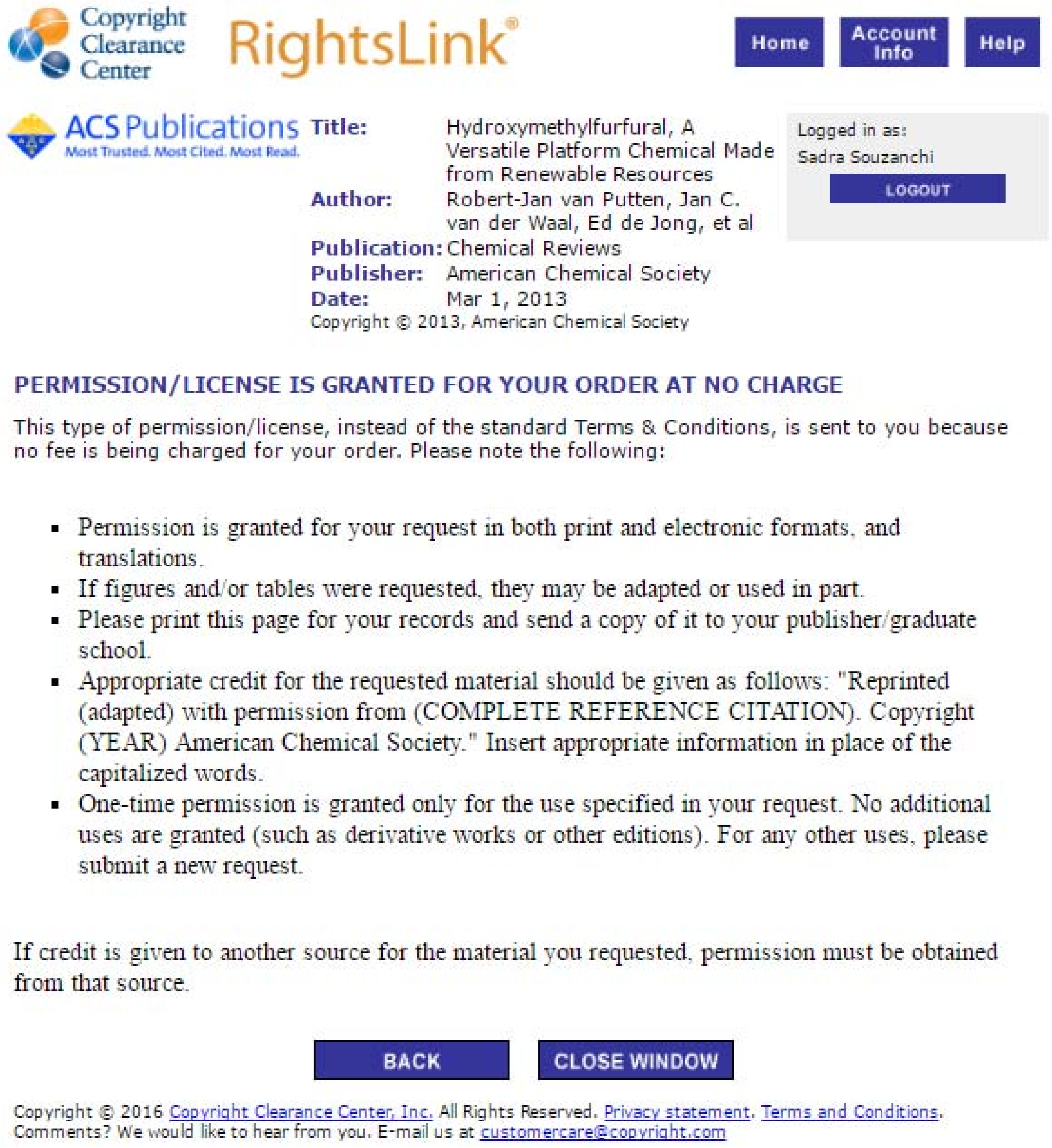

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