

BIODIESEL PRODUCTION USING AMINATED FIBROUS POLYMER  
CATALYST IN PACKED CONTINUOUS REACTOR

ALIREZA LAYEGHI MOGHADDAM

This dissertation submitted in partial fulfillment of the  
requirements for the award of the degree of  
Master of Engineering (Chemical)

Faculty of Chemical engineering  
Universiti Teknologi Malaysia

JULY 2013

*To my beloved parents and my sisters who are always supporting  
and encouraging me*

## ACKNOWLEDGEMENTS

I would like to express my great sincere appreciation to my main thesis supervisor, Professor Dr. MOHAMED MAHMOUD EL-SAYED NASEF for encouragement, guidance, critics and friendship. In addition, my grateful indeed appreciated goes to my co-supervisor, Associated Professor Ir. Dr. RAMLI BIN MAT for his guidance and advices.

My grateful thanks also extend to all academic staff and postgraduate classmates especially students in membrane and fuel cell laboratory for providing assistance at various occasions, their kindness and moral support during my study. Thanks for the friendship and memories.

Last but not least, my deepest gratitude goes to my beloved parents and my dearest sisters. Without their endless love, continued support, prays and interest I would not be able to present the same as presented here.

## ABSTRACT

A solid polymer catalyst in a form of aminated ion exchange fibers having basic functionality was prepared by amination (treatment with triethylamine) of a fibrous grafted copolymer precursor obtained by radiation induced grafting of glycidyl methacrylate (GMA) onto polyethylene (PE) fibers. The obtained aminated fibrous catalyst was characterized with Fourier transform infrared spectroscopy (FTIR), scanning electron microscope (SEM) and thermal gravimetric analysis (TGA) to confirm the presence of the functional (amine) groups. Degree of amination of 30.65% was obtained together with an amine group density of 1.89 mmol/g. The performance of the obtained fibrous polymer catalyst was tested for biodiesel production by the transesterification of triacetin with methanol using packed bed column under dynamic conditions (temperature, methanol/oil ratio and residence time). The ranges of independent variables were reaction temperature (50°C-90°C), residence time (1-5 h) and methanol:triacetin ratio (12:1-24:1). The obtained product was characterized by GC-MS to provide evidence for the conversion of triacetin to methyl acetate. The highest conversion of 90.06% was obtained at 90°C with 18:1 molar ratio and 2 h for residence time. Meanwhile, kinetic model and studies was applied. Reaction rate was calculated  $k=0.383 \text{ liter}^2 \text{ mol}^{-2} \text{ hour}^{-1}$  for the order of the reaction 2. Activation energy was calculated 46.89 kJ/mol with pre-exponential factor  $6.016 \times 10^6$  based on Arrhenius equation. The fixed bed reactor with the fibrous solid polymer catalyst set a modular process for production of biodiesel based on transesterification of triacetin. The obtained solid polymer catalyst under the optimum conditions provides sufficient conversion without purification and separation for biodiesel which might affect the properties of the product.

## ABSTRAK

Sejenis pemangkin polimer dalam bentuk serabut pertukaran ion yang diaminiasi dengan kefungisian bes telah disediakan melalui pengaminasian (rawatan dengan triethylamine) serabut kopolimer pelopor yang diperolehi menggunakan cantuman secara sinaran radiasi oleh glycidyl methacrylate (GMA) ke atas serat polyethylene (PE). Penyifatan pemangkin berserabut yang diaminiasi tersebut dilakukan dengan spektroskopi inframerah jelmaan Fourier, mikroskop elektron penskanan dan analisis gravimetri terma mengesahkan kehadiran kumpulan berfungsi. Darjah aminasi 30.65% bersama dengan ketumpatan kumpulan amina 1.89 mmol/g diperolehi. Prestasi pemangkin polimer berserabut tersebut diuji untuk pengeluaran biodiesel melalui transesterifikasi trisetin dengan metanol menggunakan ruang katil dibungkus pada kondisi-kondisi dinamik (suhu, metanol / nisbah minyak dan masa mastautin). Julat pembolehubah tak bersandar ialah suhu tindak balas ( $50^{\circ}\text{C}$ - $90^{\circ}\text{C}$ ), masa mastautin (1-5 h) dan nisbah metanol:trisetin (12:1-24:1). Produk yang diperolehi disifatkan menggunakan GC-MS untuk memberi bukti penukaran trisetin kepada methyl acetate. Penukaran tertinggi 90.06% diperolehi pada  $90^{\circ}\text{C}$  dengan 18:1 nisbah molar dan 2 jam untuk masa mastautin. Sementara itu, model kinetik dan kajian telah diaplikasikan. Kadar tindakbalas dikira,  $k=0.383 \text{ mol}^2\text{liter}^{-2}\text{jam}^{-1}$  untuk order tindak balas 2. Tenaga pengaktifan dikira 46.89 kJ / mol dengan faktor pra eksponen  $6.016 \times 10^6$  berdasarkan persamaan Arrhenius. Reaktor katil tetap berisi pemangkin polimer berserabut menetapkan satu proses bermodul untuk pengeluaran biodiesel berdasarkan transesterifikasi trisetin. Pemangkin polimer yang diperolehi dibawah keadaan optimum memberikan penukaran mencukupi tanpa penulenan dan pemisahan untuk biodiesel yang mungkin mempengaruhi sifat produk akhir.

## TABLE OF CONTENTS

CHAPTER NO.	TITLE	PAGE
	<b>DECLARATION</b>	II
	<b>DEDICATION</b>	III
	<b>ACKNOWLEDGEMENTS</b>	IV
	<b>ABSTRACT</b>	V
	<b>ABSTRAK</b>	VI
	<b>TABLE OF CONTENTS</b>	VII
	<b>LIST OF TABLE</b>	X
	<b>LIST OF FIGURE</b>	XI
	<b>LIST OF ABBREVIATION</b>	XIV
	<b>LIST OF SYMBOLS</b>	XVI
	<b>LIST OF APPENDICES</b>	XVII
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Background	1
	1.2 Biodiesel	2
	1.3 Problem Statement	4
	1.4 Research Objectives	5
	1.5 Scope of Research	5
	1.6 Dissertation Outline	6
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>7</b>
	2.1 Introduction	7
	2.2 Biodiesel Composition and Properties	8

2.3	Advantages and Disadvantages of Biodiesel	12
2.4	Biodiesel Production Methods	16
2.5	Transesterification Reaction	17
2.6	Free Fatty Acids (FFA) Reactions	19
2.7	Triacetin	20
2.8	Transesterification Parameters	21
2.9	Homogeneous Catalyst	27
2.10	Biocatalyst	30
2.11	Heterogeneous Catalyst	31
2.12	Ion Exchangers as Heterogeneous Catalyst	34
2.13	Ion Exchange Materials	35
2.14	Graft Copolymerization	40
2.15	Transesterification with Ion Exchangers	42
<b>3</b>	<b>RESEARCH METHODOLOGY</b>	<b>44</b>
3.1	Introduction	44
3.2	Experimental	46
3.2.1	Materials	46
3.2.2	Equipment	47
3.2.3	Solid Polymer Catalyst Preparation	47
3.2.4	Process Procedure	49
3.2.5	Catalyst Regeneration	51
3.2.6	Single Factor Experimental Design	51
3.2.7	Kinetics of Reaction	53
<b>4</b>	<b>RESULTS AND DISCUSSION</b>	<b>55</b>
4.1	Introduction	55
4.2	Characterization of solid polymer catalyst	56
4.2.1	Chemical Properties of Aminated catalyst	56
4.2.2	Chemical Composition of the Aminated Catalyst	56

4.2.3	Thermal Properties of the Aminated Catalyst	59
4.2.4	Morphology of the Aminated Catalyst	60
4.3	Effect of reaction parameters	61
4.3.1	Temperature	62
4.3.2	Ratio of methanol:triacetin	63
4.3.3	Residence Time	64
4.3.4	Sampling Time	65
4.3.5	Reusability	66
4.3.6	Bed Height	67
4.3.7	Kinetics of reaction	68
<b>5</b>	<b>CONCLUSION</b>	<b>71</b>
5.1	Conclusion	71
5.2	Recommendations	72
	<b>REFERENCES</b>	<b>73</b>
	Appendix A-C	80



**LIST OF TABLE**

<b>TABLE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
2.1	FFA profiles of biodiesel (Hoekman, et al., 2012)	9
2.2	Physical/chemical properties of biodiesel (Hoekman, et al., 2012)	10
2.5	Relationship levels between biodiesel composition and properties (Hoekman, et al., 2012)	12
2.6	Comparison of diesel and biodiesel specifications	13
2.7	Methods of biodiesel production	17
2.8	Comparison of three general catalytic transesterification	27
2.9	Common functional groups of polymeric ion exchange materials	38
3.1	Specifications of Triacetin	46
3.2	Conditions and ranges of reaction parameters	52
3.3	Experimental combination runs	52
3.4	Combination runs for dependence variables	53
4.1	Initial calculation for Arrhenius equation in 50°C-90°C, 18:1 methanol:triactin ratio and 2 hours residence time based on equation 4.6	69

**LIST OF FIGURE**

<b>CHAPTER NO.</b>	<b>TITLE</b>	<b>PAGE</b>
1.1	Major Sources of Biofuels	2
1.2	Main sources of biodiesel in worldwide	3
2.1	Profiles for saturation/unsaturation biodiesel feedstock (Hoekman, et al., 2012)	8
2.2	Scheme of transesterification	17
2.3	Transesterification reaction	18
2.4	Free fatty acids (FFA) reactions	19
2.5	Reactions of Triacetin transesterification	21
2.6	Schematic diagram for transesterification variables	22
2.7	Effect of basic parameters on transesterification (Refaat, et al., 2008)	24
2.8	Schematic diagram of various transesterification catalysts	26
2.10	Acid homogeneous mechanisms	30
2.11	Alkali heterogeneous mechanisms	32
2.12	Acid heterogeneous mechanism	34
2.13	Polymer chain cross-linked with short links	37
2.14	Classifications of polymeric ion exchange	37

2.15	Structure of a)Diethylenetriamine (DETA) b)Triethylenetetramine (TETA) c)Triethylamine (TEA)	39
2.16	Density of DETA, TETA amine groups in PE-g-GMA (Ma, et al., 2011)	41
2.17	Radiation-induced graft copolymerization of GMA onto PE porous film and functionalize and modified by TE	42
3.1	Flow diagram of scope throughout the study	45
3.2	Simple flow sheet of experimental continuous transesterification with fixed bed reactor	50
4.1	FTIR of ungrafted Polyethylene fabric blank	57
4.2	FTIR of poly(GMA) grafted PE nonwoven fabric	57
4.4	FTIR spectra of a) ungrafted PE nonwoven, b) PE-g-poly(GMA) c) aminated PE-g-poly(GMA)	58
4.5	TGA results for a)ungrafted PE, b)grafted PE, c)aminated PE and d)treated aminated PE with NaOH	59
4.6	Scanning electron microscope (SEM) of (a) Polyethylene ungrafted and blank, (b) grafted PE fiber with poly(GMA), and (c) aminated poly(GMA).	61
4.7	Variation of triacetin conversion with reaction temperature. The reaction conditions are: column height: 7cm, molar ratio: 18:1 methanol:triacetin, residence time: 2h.	62
4.8	Variation of triacetin conversion with methanol:triacetin ratio. The reaction conditions are: temperature: 80°C, column height: 7cm, residence time: 2h.	63

- 4.9 Variation of triacetin conversion with residence time. The reaction conditions are: temperature: 80°C, molar ratio: 18:1 methanol:triacetin, column height: 7cm. 64
- 4.10 Variation of triacetin conversion with sampling time. The reaction conditions are: temperature: 80°C, molar ratio: 18:1 methanol:triacetin, residence time: 2h, column height: 7cm. 65
- 4.11 Variation of triacetin conversion with cycles. The reaction conditions are: temperature: 90°C, molar ratio: 18:1 methanol:triacetin, residence time: 2h, column height: 7cm. 66
- 4.12 Variation of triacetin conversion with bed height. The reaction conditions are: temperature: 80°C, molar ratio: 18:1 methanol:triacetin, flow rate: 11ml/h. 67
- 4.13  $-\ln(1 - X)$  versus time at 80°C and 18:1 methanol:ratio which does not fit liner trend-line. 68
- 4.14  $\frac{1}{(1-x)}$  versus time at 80°C and 18:1 methanol:ratio which fit polynomial trend-line with second order. 69
- 4.15 Arrhenius plot for the transesterification of triacetin using aminated PE-g-poly (GMA)-TOH. Temperature range 50-90°C and 18:1 methanol:triacetin ratio 70

**LIST OF ABBREVIATION**

ASTM	-	American society for testing and materials
B100	-	Pure biodiesel
B20	-	20% biodiesel blend with fuel
B6	-	6% biodiesel blend with fuel
CEN	-	European committee for standardization
CFFP	-	Cold filter plug point
CN	-	Cetane number
CP	-	Cloud point
DAG	-	Diacylglycerol
DETA	-	Diethylenetriamine
DMF	-	Dimethylformamide
DSC	-	Differential scanning calorimetry
EGR	-	Exhaust gas recirculation
FA	-	Fatty acid
FAME	-	Fatty acid methyl esters
FFA	-	Free fatty acid
GHG	-	Greenhouse gas
GMA	-	Glycidyl methacrylate
HHV	-	Higher heating value
LHV	-	Lower heating value
MAG	-	Monoacylglycerol
NVO	-	Neat sunflower oil
NWPE	-	Nonwoven polyethylene
PE	-	Polyethylene
PP	-	Poor point

PS	-	Polystyrene
PVF	-	Polyvinyl Fluoride
RSM	-	Response surface methodology
SCR	-	Selective catalytic reduction
SEM	-	Scanning electron microscope
TAc	-	Triacein
TAG	-	Triacylglycerol
TEA	-	Triethylamine
TETA	-	Triethylenetetramine
THF	-	Tetrahydrofuran
Tw	-	Polyoxyethylene sorbitan monolaurate
WVOD	-	Domestic waste oil
WVOR	-	Fast food restaurant waste oil

**LIST OF SYMBOLS**

A	-	Alcohol
D	-	Di-glyceride
d	-	Inner column diameter
$D_g$	-	Degree of grafting
E	-	Free acid ester
h	-	Bed height
$M_a$	-	Molecular weight of TEA
$M_G$	-	molecular weight of GMA
S ( $H^+$ )	-	Cation exchange resin
S(OH)	-	Anion exchange resin
T	-	Triglyceride
$W_a$	-	Mass of the aminated PE-g-GMA
$W_i$	-	Polymer weight after grafting
$W_o$	-	Polymer weight before grafting
$\tau$	-	Residence time

**LIST OF APPENDICES**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Tables for Introduction and Literature Review	80
B	Sample Calculation for Amination Quantifying	85
C	Sample Calculation for Conversion	86



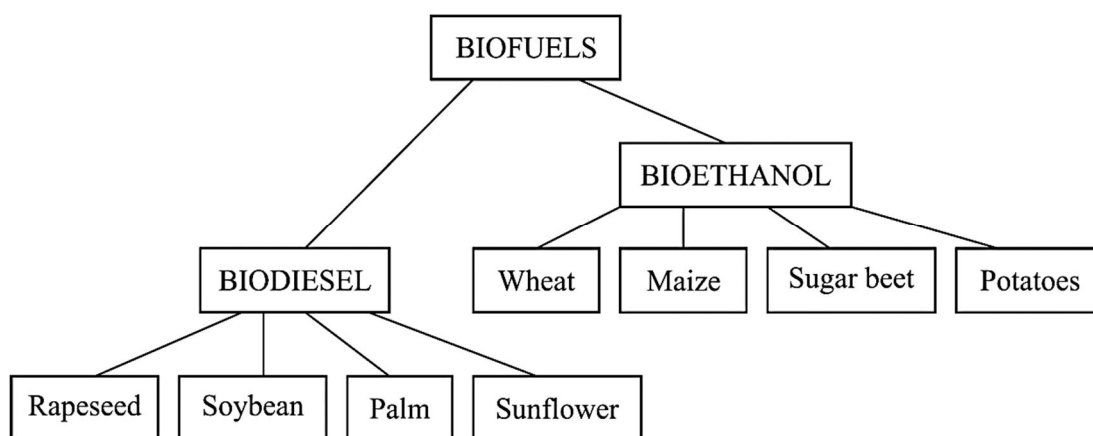
## CHAPTER 1

### INTRODUCTION

#### 1.1 Background

The quick development of population, transport and urbanization is today's energy crisis. Fossil fuel as a non-renewable source, chips in 80% of the world's energy demand (Demain, 2009; Huang et al., 2012; Ng et al., 2010). Due to this unsustainable energy system, demand for other renewable power/fuel is increasing. Major alternatives to fossil fuels are nuclear power and hydroelectricity (Cseke et al., 2009). Biofuels are coming out as one of the green option for alternative and renewable energy. In developed countries there is an increasing trend towards the use of modern technologies and efficient bioenergy systems using a range of biofuels, which are more economical than fossil fuels. Biofuels are produced from biomass. Biomass is biological material come from living, or recently living, organisms. Biofuel refers to solid, liquid or gas material for the transport sector that are predominantly produced from biomass or organic matter. Biofuels offer many benefits, including sustainability, reduction of greenhouse gas emissions (Bessou et al., 2011; Demain, 2009). According to the state of the biofuels at room temperature, they can be classified easily. There are gaseous bio-fuels, like biogas from different sources and syngas (coal gas); liquid biofuels including biodiesel, bioethanol, vegetable oil and bio-oil; and solid biofuels such as wood and charcoal. Bioethanol and biodiesel are two general biomass products in liquid form that can replace gasoline and diesel fuel (Figure 1.1). Bioethanol is obtained from the aerobic fermentation of carbohydrate-rich biomass, often used in blends. In plant materials,

carbohydrates (e.g. cellulose and hemicelluloses) can be hydrolyzed and formed into sugars. The fermentation is an anaerobic biological process in which the sugars are converted into alcohol by the action of microorganisms, generally yeast. The obtained alcohol is ethanol. The reaction between animal fat or vegetable oil with alcohol produces biodiesel. This reaction is called transesterification (Bessou, et al., 2011; Cseke, et al., 2009; Demain, 2009; Huang, et al., 2012; Murphy, 2011; Ng, et al., 2010; Romano and Sorichetti, 2011; Roy, 2007).



**Figure 1.1** Major Sources of Biofuels

## 1.2 Biodiesel

Many years before Rudolf Diesel's presented his diesel engine, oil crops and animal fats have been used as sources of fuels, for a long time. Vegetable oil's Transesterification was done by J. Patrick and E. Duffy, in early 1853. 40 years later (on August 10, 1893), Mr. Diesel invited a cylinder with a flywheel at its base, made from iron in 3meter which use up its own power for the first time (Cseke, et al., 2009). Diesel ran his car on pure peanut oil at the 1901 in Paris (Murphy, 2011). Biodiesel as a clean burning fuel for diesel engines is made from internally produced, renewable fats and oils like sunflower oil, without aromatic or sulfur compounds. Most of the Plant oils are contained long-chain triacylglycerol which can be used directly as fuels or lubricants, while it is usable to a few of engine types. On the other hand, the triacylglycerol can be formed to methyl esters somehow similar to

petroleum hydrocarbons, and glycerol. Recently environmental assesses have made effect and decreased price differences for vegetable oils as an alternative source. Although the World use fossil petroleum, propensity to vegetable oils as fuels in inner combustion engines were afforded in several countries between 1920s and 1930 (Cseke, et al., 2009). Biodiesel can be used in engines without adjustment or with blending. It is a great alternative choice for our environment due to reducing dependence on our fossil fuel and bringing more value and credit for agricultural product markets. As shown in Figure 1.2, the usage of feedstock related with local region and climate conditions. Therefore different soils are using different types of oil. At present, the dominant feed stocks are rapeseed oil in Europe, soybean oil in the U.S., and palm oil in South East Asia. Animal fats (especially beef tallow) and used cooking oil (also known as yellow grease) are small but important market for biodiesel in many places. Other vegetable oils with a real or potential commercial interest that supply biodiesel stocks are canola, coconut, corn, sunflower and jatropa (Huang, et al., 2012).



**Figure 1.2** Main sources of biodiesel in worldwide

### 1.3 Problem Statement

The most important obstacle for biodiesel production is feedstock and catalyst for the process which more expensive than the petroleum diesel. Technologies for Biodiesel processes will cost-effective, in case of reduction material costs. In addition, according to the demands for renewable fuel instead of petroleum, there is no processes which can provide the high production of biodiesel in sufficient quality, quantity and production speed to be acceptable for total demands and Industrial scale. Pyrolysis has some drawbacks include corrosivity, low calorific value, high viscosity characteristic of aging, making improper crude biodiesel to its direct use as an alternative fuel. Most of the produced biodiesel are blended with petro-diesel. Every day, scientists introduce new methods and technologies, but biodiesels still is not completely substitutable choice for fuels and need more qualifications in processes and materials that use.

Upgrade catalyst methods give a low yield improved oil and could produce undesirable products (e.g., deposition of coke on the catalyst surface), giving high cost of product recovery. According to this, for known feed-stocks, oils and fats and specific technologies for reaction, catalyst and reaction variables still have a wide variety to improve biodiesel production.

Solid polymer catalyst as a heterogeneous catalyst can provide many advantages to overcome these problems. Solid catalysts are recyclable and have longer lifetime for processes. Usually they are used for membrane processes to remove impurities like heavy metals as ion exchange resins. With strong functional group on solid catalysts, it can be used in transesterification reactions as membrane too. They provide easy separation process, simple ester and glycerol purification and make the process potentially cheaper. In addition homogenous catalyst must be separated from products which can effect products, while heterogeneous catalyst is not needed. Anion ion exchange fibrous for lower crosslinking density and smaller particle size comparing to cation form, is superior option due to high basic activity, selectivity and non-corrosiveness provide high conversion and reaction rate. Polyethylene grafted by Glycidyl methacrylate as a common base polymer, modified

by Triethylamine as a strong ammonium function group was used as an efficient solid polymer catalyst for biodiesel production.

#### **1.4 Research Objectives**

The main objective of this research is to explore the performance of the obtained catalyst for biodiesel production under dynamic conditions. The objectives of this study are listed as below:

- i. To prepare solid polymer catalyst by activating the precursor by animation reaction.
- ii. To characterize the obtained solid polymer catalyst.
- iii. To investigate the effects of reaction parameters on the conversion of triacetin to biodiesel in a packed bed column system under dynamic conditions.

#### **1.5 Scope of Research**

To achieve the objectives of this study, the following scope of work was pursued.

- i. Firstly, NWPE which was grafted with glycidyl methacrylate (GMA) was modified by triethylamine solution at 90°C for 24 h to introduce amine groups. The aminated catalyst was then alkalized by a treatment with NaOH.
- ii. The prepared solid polymer catalyst was characterized by Fourier transform infrared spectroscopy (FTIR), scanning electron microscope (SEM) and thermal gravimetric analysis (TGA) to confirm the incorporation of the amine group on catalyst.

- iii. Catalyst was tested under various conditions to evaluate the catalyst performance in continuous mode. Catalyst was cut into discs and inserted into the column to have a packed bed. Temperature, residence time and ratio in specific ranges were examined to analyze the conversion of the reaction. Temperature from 50°C to 90°C, molar ratio from 12:1 to 24:1 methanol:triacetin and residence time from 1 hour to 5 hours for 7 cm catalyst in the column were analyzed for single factor analysis.
- iv. Determination of the best reaction combination for obtaining the highest conversion. Dependence variables like sampling time in range of 2-10h, reusability of the catalyst after 40times cycles and bed height of the catalyst in the column in range of 2-11cm were analyzed. Kinetic model was obtained to calculate the reaction rate order, reaction rate constant and activation energy of triacetin transesterification with a functionalized aminated PE-g-GMA solid polymer catalyst.

## **1.6 Dissertation Outline**

This study investigates the preparation of the solid polymer catalyst by amination and its activity by transesterification of the triacetin. Chapter 1 introduced the biodiesel and transesterification reactions. Meanwhile it covered the problem statement, the objectives and scope of study. Chapter 2 fully covered the biodiesel properties and specifications. Furthermore, different methods for transesterification was fully observed and ion exchange materials were introduced. Finally ion exchange transesterification was introduced. Chapter 3 introduced the methodologies of the research step-by-step to achieve the objectives. Chapter 4 included the results and the discussion including interpretation of the findings and comparing with prior studies. Finally chapter 5 contained the conclusions and recommendation for further studies.

**REFERENCES**

- Alchin, D. (2000). ION EXCHANGE RESINS. XIII-Water-D-Ion Exchange Resins, 1-7.
- Atabani, A. E., Silitonga, A. S., Badruddin, I. A., Mahlia, T. M. I., Masjuki, H. H. and Mekhilef, S. (2012). A comprehensive review on biodiesel as an alternative energy resource and its characteristics. *Renewable and Sustainable Energy Reviews*, 16(4), 2070-2093.
- Atadashi, I. M., Aroua, M. K., Aziz, A. R. A. and Sulaiman, N. M. N. (2012). Production of biodiesel using high free fatty acid feedstocks. *Renewable and Sustainable Energy Reviews*, 16(5), 3275-3285.
- Banavali, R., Schultz, A. K., Hanlon, R. T. and Jerabek, K. (2008). Heterogeneous Catalyst and Process for the Production of Biodiesel from High Free-Fatty Acid-Containing Feedstocks *Catalysis of Organic Reactions* (pp. 279-289): CRC Press.
- Banković-Ilić, I. B., Stamenković, O. S. and Veljković, V. B. (2012). Biodiesel production from non-edible plant oils. *Renewable and Sustainable Energy Reviews*, 16(6), 3621-3647.
- Bessou, C., Ferchaud<sup>2</sup>, F., Gabrielle<sup>3</sup>, B. and Mary<sup>2</sup>, B. (2011). Biofuels, greenhouse gases and climate change. A review. *Agron. Sustain. Dev.*, 31.
- Boro, J., Deka, D. and Thakur, A. J. (2012). A review on solid oxide derived from waste shells as catalyst for biodiesel production. *Renewable and Sustainable Energy Reviews*, 16(1), 904-910.
- Buasri, A., Chaikut, N., Loryuenyong, V., Rodklum, C., Chaikwan, T. and Kumphan, N. (2012). Continuous Process for Biodiesel Production in Packed Bed Reactor from Waste Frying Oil Using Potassium Hydroxide Supported on *Jatropha curcas* Fruit Shell as Solid Catalyst. *Applied Sciences*, 2(3), 641-653.
- Chen, W. and Qu, B. (2003). Structural characteristics and thermal properties of PE-g-MA/MgAl-LDH exfoliation nanocomposites synthesized by solution intercalation. *Chemistry of Materials*, 15(16), 3208-3213.

- Cheng, Y., Feng, Y., Ren, Y., Liu, X., Gao, A., He, B., et al. (2012). Comprehensive kinetic studies of acidic oil continuous esterification by cation-exchange resin in fixed bed reactors. *Bioresource Technology*, 113(0), 65-72.
- Choi, S.-H., Hwang, Y.-M. and Lee, K.-P. (2003). Separation of proteins on polymeric stationary phases grafted with various amine groups. *Journal of Chromatography A*, 987(1-2), 323-330.
- Choi, S.-H., Jeong, Y.-H., Ryoo, J.-J. and Lee, K.-P. (2001). Desalination by electro dialysis with the ion-exchange membrane prepared by radiation-induced graft polymerization. *Radiation Physics and Chemistry*, 60(4-5), 503-511.
- Chouhan, A. P. S. and Sarma, A. K. (2011). Modern heterogeneous catalysts for biodiesel production: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 15(9), 4378-4399.
- Co, C. E. T., Tan, M. C., Diamante, J. A. R., Yan, L. R. C., Tan, R. R. and Razon, L. F. (2011). Internal mass-transfer limitations on the transesterification of coconut oil using an anionic ion exchange resin in a packed bed reactor. *Catalysis Today*, 174(1), 54-58.
- Cseke, L. J., Podila, G. K., Kirakosyan, A. and Kaufman, P. B. (2009). *Plants as Sources of Energy (Vol. Part 2)*.
- Demain, A. L. (2009). *Biosolutions to the energy problem (Vol. Volume 36, Number 3, )*.
- Du, W. and Liu, D.-H. (2012). *Biodiesel From Conventional Feedstocks*.
- Endalew, A. K., Kiros, Y. and Zanzi, R. (2011). Inorganic heterogeneous catalysts for biodiesel production from vegetable oils. *Biomass and Bioenergy*, 35(9), 3787-3809.
- Gupta, B., Kanda, V., Sethi, P. and Saxena, S. (2008). Development of ion exchanger by modification of polypropylene fibre waste using radiation-induced graft polymerization of acrylamide and subsequent animation. *Indian Journal of Fibre and Textile Research*, 33(4), 431-437.



- Harding, K. G., Dennis, J. S., Blottnitz, H. v. and Harrison, S. T. L. (2008). A life-cycle comparison between inorganic and biological catalysis for the production of biodiesel. *Journal of Cleaner Production*, 16(13), 1368-1378.
- Helwani, Z., Othman, M. R., Aziz, N., Fernando, W. J. N. and Kim, J. (2009). Technologies for production of biodiesel focusing on green catalytic techniques: A review. *Fuel Processing Technology*, 90(12), 1502-1514.
- Hoekman, S. K., Broch, A., Robbins, C., Cenicerros, E. and Natarajan, M. (2012). Review of biodiesel composition, properties, and specifications. *Renewable and Sustainable Energy Reviews*, 16(1), 143-169.
- Huang, D., Zhou, H. and Lin, L. (2012). Biodiesel: an Alternative to Conventional Fuel. *Energy Procedia*, 16, Part C(0), 1874-1885.
- Islam, A., Taufiq-Yap, Y. H., Chu, C.-M., Chan, E.-S. and Ravindra, P. (2012). Studies on design of heterogeneous catalysts for biodiesel production. *Process Safety and Environmental Protection*, (0).
- Kang, P. H., Jeun, J. P., Chung, B. Y., Kim, J. S. and Nho, Y. C. (2007). Preparation and characterization of glycidyl methacrylate (GMA) grafted Kapok fiber by using radiation induced-grafting technique. *Journal of Industrial and Engineering Chemistry*, 13(6), 956-958.
- Kumanayaka, T. O., Parthasarathy, R. and Jollands, M. (2010). Accelerating effect of montmorillonite on oxidative degradation of polyethylene nanocomposites. *Polymer Degradation and Stability*, 95(4), 672-676.
- Kunita, M. H., Rinaldi, A. W., Giroto, E. M., Radovanovic, E., Muniz, E. C. and Rubira, A. F. (2005). Grafting of glycidyl methacrylate onto polypropylene using supercritical carbon dioxide. *European Polymer Journal*, 41(9), 2176-2182.
- Leung, D. Y. C., Wu, X. and Leung, M. K. H. (2010). A review on biodiesel production using catalyzed transesterification. *Applied Energy*, 87(4), 1083-1095.

- Limpanuparb, T., Punyain, K. and Tantirungrotechai, Y. (2010). A DFT investigation of methanolysis and hydrolysis of triacetin. *Journal of Molecular Structure: THEOCHEM*, 955(1–3), 23-32.
- Liu, C.-X., Zhang, S.-P., Su, Z.-G. and Wang, P. (2012). LiCl-induced improvement of multilayer nanofibrous lipase for biodiesel synthesis. *Bioresource Technology*, 103(1), 266-272.
- López, D. E., Jr, J. G. G., Bruce, D. A. and Lotero, E. (2005). Transesterification of triacetin with methanol on solid acid and base catalysts. *Applied Catalysis A: General*, 295(2), 97-105.
- Ma, H., Yao, S., Li, J., Cao, C. and Wang, M. (2011). A mild method of amine-type adsorbents syntheses with emulsion graft polymerization of glycidyl methacrylate on polyethylene non-woven fabric by pre-irradiation. *Radiation Physics and Chemistry*, (0).
- Ma, H., Yao, S., Li, J., Cao, C. and Wang, M. (2012). A mild method of amine-type adsorbents syntheses with emulsion graft polymerization of glycidyl methacrylate on polyethylene non-woven fabric by pre-irradiation. *Radiation Physics and Chemistry*, 81(9), 1393-1397.
- Marchetti, J. M. (2012). A summary of the available technologies for biodiesel production based on a comparison of different feedstock's properties. *Process Safety and Environmental Protection*, 90(3), 157-163.
- Marchetti, J. M., Miguel, V. U. and Errazu, A. F. (2007). Possible methods for biodiesel production. *Renewable and Sustainable Energy Reviews*, 11(6), 1300-1311.
- Merle, G., Wessling, M. and Nijmeijer, K. (2011). Anion exchange membranes for alkaline fuel cells: A review. *Journal of Membrane Science*, 377(1–2), 1-35.
- Moser, B. R. (2011). *Biodiesel Production, Properties, and Feedstocks*.
- Mufrodi, Z., Rochmadi, S. and Budiman, A. (2012). Chemical Kinetics for Synthesis of Triacetin from Biodiesel Byproduct Retrieved April 1, 2012, 2012, from <http://www.ccsenet.org/journal/index.php/ijc/article/view/13584/10915>

- Murphy, D. J. (2011). Oil Crops as Potential Sources of Biofuels. Division of Biological Sciences, 269-282.
- Nasef, M. M. (2009). Preparation and characterization of cation exchange resins based on locally-fabricated polyethylene pellets.
- Nasef, M. M. and Hegazy, A. E.-S. (2004). Preparation and applications of ion exchange membranes by radiation-induced graft copolymerization of polar monomers onto non-polar films. *Progress in Polymer Science*, 29(6), 499-561.
- Naushad, M. (2009). Inorganic and Composite Ion Exchange Materials and their Applications (Review). *Ion Exchange Letters* 2, 1-14.
- Ng, J.-H., Ng, H. K. and Gan, S. (2010). Recent trends in policies, socioeconomy and future directions of the biodiesel industry (Vol. Volume 12, Number 3).
- Refaat, A. A. (2010). Different techniques for the production of biodiesel from waste vegetable oil. *Int. J. Environ. Sci. Tech.*, 7 (1), 183-213.
- Refaat, A. A. (2011). Biodiesel production using solid metal oxide catalysts. *Int. J. Environ. Sci. Tech.*, 8 (1), 203-221.
- Refaat, A. A., Attia, N. K., Sibak, H. A., ElSheltawy, S. T. and ElDiwani, G. I. (2008). Production optimization and quality assessment of biodiesel from waste vegetable oil. *Int. J. Environ. Sci. Tech.*, 5 (1), 75-82.
- Ren, Y., He, B., Yan, F., Wang, H., Cheng, Y., Lin, L., et al. (2012). Continuous biodiesel production in a fixed bed reactor packed with anion-exchange resin as heterogeneous catalyst. *Bioresource Technology*, 113(0), 19-22.
- Rohidas, B., Dheerendra, S., Purshottam, G., Anuradda, D. G. and Sanjay, M. Synthesis of biodiesel in continuous packed bed reactor using ZnO/ZSM-5 as a heterogeneous catalyst, from [http://conf.ti.kviv.be/iscre22/programme/10-ABSTRACT-519-ISCRE22\\_Rohidas%20Bhoi\\_IITBombay.pdf](http://conf.ti.kviv.be/iscre22/programme/10-ABSTRACT-519-ISCRE22_Rohidas%20Bhoi_IITBombay.pdf)
- Romano, S. D. and Sorichetti, P. A. (2011). Introduction. *Green Energy and Technology, (Dielectric Spectroscopy in Biodiesel Production and Characterization)*, 1-6.

- Roy, A. H. (2007). *Fertilizers and Food Production (Vol. Part 2)*.
- Seko, N., Bang, L. T. and Tamada, M. (2007). Syntheses of amine-type adsorbents with emulsion graft polymerization of glycidyl methacrylate. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 265(1), 146-149.
- Sharma, R. K. (2012). A study in thermal properties of graft copolymers of cellulose and methacrylates. *Advances in Applied Science Research Volume 3 :Issue 6* : 2012, from <http://pelagiaresearchlibrary.com/advances-in-applied-science/vol3-iss6/AASR-2012-3-6-3961-3969.pdf>
- Shibasaki-Kitakawa, N., Honda, H., Kuribayashi, H., Toda, T., Fukumura, T. and Yonemoto, T. (2007). Biodiesel production using anionic ion-exchange resin as heterogeneous catalyst. *Bioresource Technology*, 98(2), 416-421.
- Sokker, H. H., Badawy, S. M., Zayed, E. M., Eldien, F. A. N. and Farag, A. M. (2009). Radiation-induced grafting of glycidyl methacrylate onto cotton fabric waste and its modification for anchoring hazardous wastes from their solutions. *Journal of Hazardous Materials*, 168(1), 137-144.
- Song, C., Qi, Y., Deng, T., Hou, X. and Qin, Z. (2010). Kinetic model for the esterification of oleic acid catalyzed by zinc acetate in subcritical methanol. *Renewable Energy*, 35(3), 625-628.
- Sun, P., Sun, J., Yao, J., Zhang, L. and Xu, N. (2010). Continuous production of biodiesel from high acid value oils in microstructured reactor by acid-catalyzed reactions. *Chemical Engineering Journal*, 162(1), 364-370.
- Tesser, R., Casale, L., Verde, D., Serio, M. D. and Santacesaria, E. (2010). Kinetics and modeling of fatty acids esterification on acid exchange resins. *Chemical Engineering Journal*, 157(2-3), 539-550.
- Vyas, A. P., Shukla, P. H. and Subrahmanyam, N. (2011, 08-10 DECEMBER, 2011). Production of Biodiesel using Homogeneous Alkali Catalyst and its Effect on Vehicular Emission, from [http://nuicone.org/site/common/proceedings/Chemical/oral/CH\\_11.pdf](http://nuicone.org/site/common/proceedings/Chemical/oral/CH_11.pdf)

- Yao, J., Ji, L., Sun, P., Zhang, L. and Xu, N. (2010). Low boiling point organic amine-catalyzed transesterification of cottonseed oil to biodiesel with trace amount of KOH as co-catalyst. *Fuel*, 89(12), 3871-3875.
- Zabeti, M., Daud, W. M. A. W. and Aroua, M. K. (2009). Activity of solid catalysts for biodiesel production: A review. *Fuel Processing Technology*, 90(6), 770-777.
- Zhang, H., Ding, J., Qiu, Y. and Zhao, Z. (2012). Kinetics of esterification of acidified oil with different alcohols by a cation ion-exchange resin/polyethersulfone hybrid catalytic membrane. *Bioresource Technology*, 112(0), 28-33.
- Zhang, L., Guo, W., Liu, D., Yao, J., Ji, L., Xu, N., et al. (2008). Low Boiling Point Organic Amine-Catalyzed Transesterification for Biodiesel Production. *Energy & Fuels*, 22(2), 1353-1357.