

IN-SITU CATALYTIC PYROLYSIS REACTION OF SUGARCANE BAGASSE  
OVER NICKEL-CERIUM/HZSM-5 FOR ENHANCED HYDROCARBONS IN  
PYROLYSIS OIL

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I would like to dedicate my thesis to my beloved mother and father

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## ABSTRACT

The catalytic of oxygenated pyrolysis vapour over HZSM-5 catalyst is of the preferred method to enhance the quality of pyrolysis oil. However, the content of  $C_6 - C_8$  hydrocarbons in pyrolysis oil produced by this method is still low. Thus, the main aim of this study is to investigate the in-situ catalytic of oxygenated pyrolysis vapours from sugarcane bagasse into enhanced  $C_6 - C_8$  hydrocarbons in pyrolysis oil over nickel-cerium/HZSM-5 catalyst. The first aim was to synthesize catalysts via incipient wetness impregnation and characterize via X-ray diffraction, field emission scanning electron microscopy-energy dispersive X-ray, Brunauer Emmett Teller, Fourier transform infrared, and temperature programmed desorption of ammonia. The HZSM-5 was fixed at 94 wt.%, while the balance 6 wt.% was impregnated at nickel to cerium mass ratios as follows: 1:5 (NC1), 2:4 (NC2), 3:3 (NC3), 4:2 (NC4), and 5:1 (NC5). The second aim was to investigate the performance of catalyst in the catalytic of oxygenated pyrolysis vapours into enhanced  $C_6 - C_8$  hydrocarbons via in-situ fixed bed reactor at pyrolysis reaction temperature ranging from 400 – 600 °C. The catalyst to biomass mass ratios was as follows: 0.5:1.0 (CB1), 1.0:1.0 (CB2), 1.5:1.0 (CB3), 2.0:1.0 (CB4), 2.5:1.0 (CB5), and 3.0:1.0 (CB6). The results show that the in-situ catalytic of oxygenated pyrolysis vapours were significantly influenced by pyrolysis reaction temperatures, catalyst to biomass mass ratios, and nickel to cerium mass ratios. The highest total contents of  $C_6 - C_8$  hydrocarbons in pyrolysis oil (8.82%) is attained at pyrolysis reaction temperature of 500 °C, catalyst to biomass mass ratio of 1:1, and nickel to cerium mass ratio of 3:3. The third aim was to optimize the process parameters via response surface methodology, in which the optimized  $C_6 - C_8$  hydrocarbons in pyrolysis oil (8.90%) can be achieved at pyrolysis reaction temperature of 505 °C, catalyst to biomass mass ratio of 1.1:1.0, nickel to cerium mass ratio of 3.14:2.86. The final aim was to perform the kinetic analysis of catalytic pyrolysis process. For the kinetic analysis, the catalytic pyrolysis has achieved higher activation energy (34.02 – 122.23 kJ/mol) than the non-catalytic pyrolysis (17.17 – 66.90 kJ/mol) using the Flynn-Wall-Ozawa method. The reaction mechanisms of non-catalytic and catalytic pyrolysis obtained via the Coats-Redfern method follows power law ( $n = 1$ ) and chemical reaction ( $n = 2$ ) respectively. Finally, the catalytic of oxygenated pyrolysis vapours over nickel-cerium/HZSM-5 catalyst can produce high contents of hydrocarbon fuel directly from sugarcane bagasse.

## ABSTRAK

Pemangkin wap pirolisis oksigen dengan menggunakan mangkin HZSM-5 adalah kaedah pilihan untuk meningkatkan kualiti minyak pirolisis. Bagaimanapun, kandungan hidrokarbon  $C_6 - C_8$  dalam minyak pirolisis yang terhasil dengan kaedah ini adalah masih rendah. Oleh itu, matlamat utama kajian ini adalah untuk mengkaji in-situ pemangkin wap pirolisis oksigen daripada hampas tebu ke hidrokarbon  $C_6 - C_8$  dalam minyak pirolisis menggunakan mangkin nikel-serium/HZSM-5. Matlamat pertama adalah untuk menghasilkan mangkin melalui impregnasi basah dan dicirikan melalui belauan sinar-X, mikroskop penyebaran emisi medan elektron-sinar-X penyebaran tenaga, Brunauer Emmett Teller, spektroskopi infra-merah jelmaan Fourier, dan penyahjerapan ammonia berprogram suhu. HZSM-5 telah ditetapkan pada 94 % berat, manakala 6 % berat adalah berdasarkan pada nisbah jisim nikel kepada serium: 1:5 (NC1), 2:4 (NC2), 3:3 (NC3), 4:2 (NC4), dan 5:1 (NC5). Matlamat kedua adalah untuk mengkaji prestasi mangkin dalam proses peningkatan wap pirolisis oksigen ke hidrokarbon  $C_6 - C_8$  dalam reaktor padatan tetap in-situ pada suhu tindak balas pirolisis iaitu 400 – 600 °C. Nisbah jisim mangkin kepada biojisim ialah 0.5:1.0 (CB1), 1.0:1.0 (CB2), 1.5:1.0 (CB3), 2.0:1.0 (CB4), 2.5:1.0 (CB5), dan 3.0:1.0 (CB6). Hasil keputusan menunjukkan bahawa in-situ pemangkin wap pirolisis oksigen amat dipengaruhi oleh suhu tindak balas pirolisis, nisbah jisim mangkin kepada biojisim, dan nisbah jisim nikel kepada serium. Kandungan hidrokarbon  $C_6 - C_8$  yang tertinggi dalam minyak pirolisis (8.82%) telah dicapai pada suhu tindak balas pirolisis 500 °C, nisbah jisim mangkin kepada biojisim iaitu 1:1, dan nisbah jisim nikel kepada serium iaitu 3:3. Matlamat ketiga ialah untuk mengoptimumkan parameter proses melalui kaedah gerak balas permukaan yang telah mengoptimumkan hidrokarbon  $C_6 - C_8$  dalam minyak pirolisis (8.90%) boleh dicapai pada suhu tindak balas pirolisis 505 °C, nisbah jisim mangkin kepada biojisim iaitu 1.1:1.0, nisbah jisim nikel kepada serium iaitu 3.14:2.86. Matlamat akhir adalah untuk melaksanakan analisis kinetik proses pirolisis mangkin. Pirolisis bermangkin telah mencapai tenaga pengaktifan yang tinggi (34.02 – 122.23 kJ/mol) berbanding pirolisis biojisim (17.17 – 66.90 kJ/mol) menggunakan kaedah Flynn-Wall-Ozawa. Mekanisme tindak balas pirolisis tanpa bermangkin dan bermangkin diperoleh melalui kaedah Coats-Redfern masing-masing adalah mematuhi hukum kuasa ( $n = 1$ ) dan tindak balas kimia ( $n = 2$ ). Akhirnya, peningkatan wap pirolisis oksigen menggunakan mangkin nikel-serium/HZSM-5 boleh menghasilkan bahan api hidrokarbon yang tinggi daripada hampas tebu.

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## LIST OF ABBREVIATIONS

A	-	Pre-exponential Factor
BBD	-	Box-Behnken design
BET	-	Brunauer Emmett Teller
Ce	-	Cerium
CR	-	Coats-Redfern
DTG	-	Differential Thermogravimetric
E	-	Activation Energy
FESEM-EDX	-	Field Emission Scanning Electron Microscopy- Energy Dispersive X-ray
FTIR	-	Fourier Transform Infrared Spectroscopy
FWO	-	Flynn-Wall-Ozawa
GC/MS	-	Gas Chromatography/Mass Spectrometry
HZSM-5	-	Hydrogen exchanged Zeolite Socony Mobile Five
MSE	-	Mean Squared Error
NC0	-	HZSM-5 Catalyst
NC1	-	1 wt.% Ni : 5 wt.% Ce : 94 wt.% HZSM-5
NC2	-	2 wt.% Ni : 4 wt.% Ce : 94 wt.% HZSM-5
NC3	-	3 wt.% Ni : 3 wt.% Ce : 94 wt.% HZSM-5
NC4	-	4 wt.% Ni : 2 wt.% Ce : 94 wt.% HZSM-5
NC5	-	5 wt.% Ni : 1 wt.% Ce : 94 wt.% HZSM-5
Ni	-	Nickel
RSM	-	Response Surface Methodology
SB	-	Sugarcane Bagasse
SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	-	Silica to Alumina Mole Ratio



TGA	-	Thermogravimetric Analysis
TG	-	Thermogravimetric
TPD-NH <sub>3</sub>	-	Temperature Programmed Desorption Ammonia
TPO	-	Temperature-Programmed Oxidation
XRD	-	X-ray Diffraction

## LIST OF SYMBOLS

$^{\circ}\text{C}$	-	Degree Celsius
K	-	Kelvin Degree
$R^2$	-	The Determination of Coefficient
wt. %	-	Weight Percent in Dry Basis
nm	-	Nanometre
mm	-	Millimetre
min	-	Minute
mL	-	Milliliter
g	-	Gram
$\mu\text{L}$	-	Microliter
$\mu\text{m}$	-	Micrometre
m/z	-	Mass/Charge Number of Ions
$\beta_1, \beta_2, \beta_3$	-	The Linear Terms
$\beta_{11}, \beta_{22}, \beta_{33}$	-	The Squared Terms
$\beta_{12}, \beta_{13}, \beta_{23}$	-	The Interaction Terms
$\beta_0$	-	The Offset Term
$X_1$	-	The Coded Forms of Input Variable for Pyrolysis Reaction Temperature
$X_2$	-	The Coded Forms of Input Variable for Catalyst to Biomass Mass Ratio
$X_3$	-	The Coded Forms of Input Variable for Nickel to Cerium Mass Ratio
Y	-	The Predicted Total Contents of $\text{C}_6 - \text{C}_8$ Hydrocarbons in Pyrolysis Oil
$^{\circ}\text{C}/\text{min}$	-	Heating Rate/Ramping Rate

**LIST OF APPENDICES**

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## CHAPTER 1

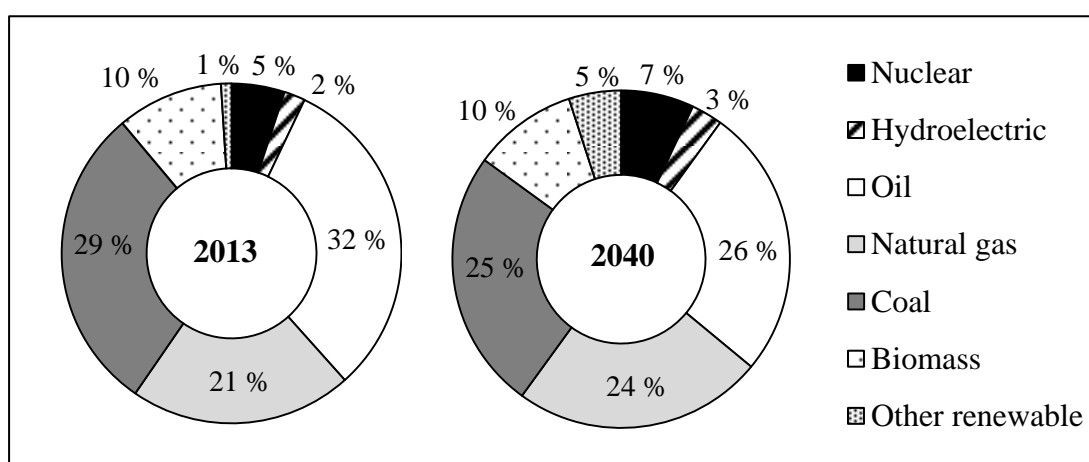
### INTRODUCTION

#### 1.1 Research Background

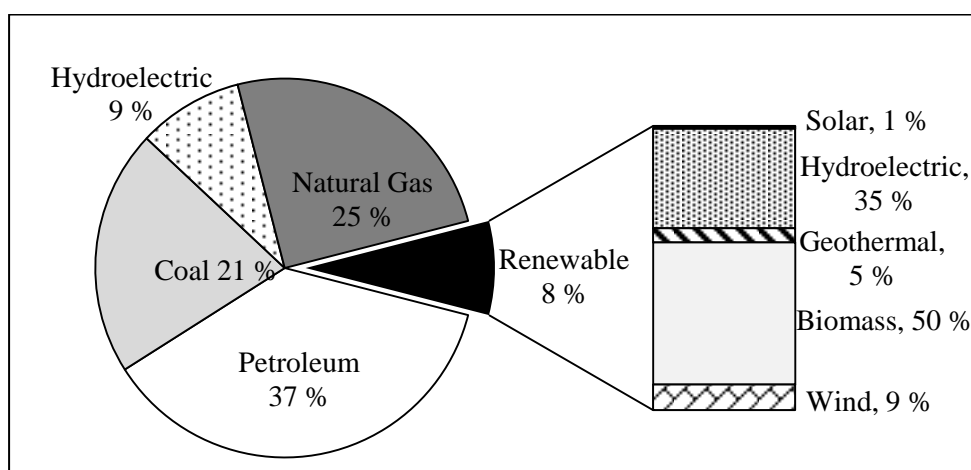
The C<sub>6</sub> – C<sub>8</sub> hydrocarbons have potential market value as gasoline enhancers in the petrochemical industry specifically for the transportation sector (Escola *et al.*, 2012). It is because the C<sub>6</sub> – C<sub>8</sub> hydrocarbons have a characteristic of high volatility that could easily vaporise and diffuse into the combustion chamber. Moreover, the C<sub>6</sub> – C<sub>8</sub> hydrocarbons can be used as high value-added chemical feedstock to manufacture various products such as synthetic fibres, plastics, and detergents (Zheng *et al.*, 2014a). Hence, the market demands for C<sub>6</sub> – C<sub>8</sub> hydrocarbons are increasing worldwide due to their wide applications (Zhou *et al.*, 2014). Currently, these hydrocarbons are produced from petroleum feedstock and petroleum reserves around the world are depleting at a rapid rate (Li *et al.*, 2014). According to the prediction done by U.S. Energy Information Administration (2016), a 60% decrease in global energy consumption is foreseen by 2040 as shown in Figure 1.1. This situation has enhanced the exploration of renewable feedstock for the production of renewable hydrocarbons (Zhou *et al.*, 2014).

Apart of the world energy, Malaysia's main energy resources are petroleum (37 %), natural gas (25 %), coal (21 %), and hydroelectric (9 %) as shown in Figure

1.2 (Chen, 2012). Malaysia is also potential for renewable energy resources including biomass (50 %), hydroelectric (35 %), wind (9 %), geothermal (5 %), and solar (1 %) as shown in Figure 1.2. Interestingly, biomass is the only renewable source of organic carbon and hydrogen, in which can be converted into hydrocarbon fuels (Kantarelis *et al.*, 2013). Hence, among Malaysia's renewable resources, biomass is in abundance in which could be defined as attractive sustainable feedstock for the production of alternative energy. Biomass energy is the most potential renewable energy resource as an alternative to fossil fuel in producing hydrocarbons.



**Figure 1.1** Comparison of world energy consumption by source for primary energy between the year 2013 and 2040 (International Energy Outlook, 2016)

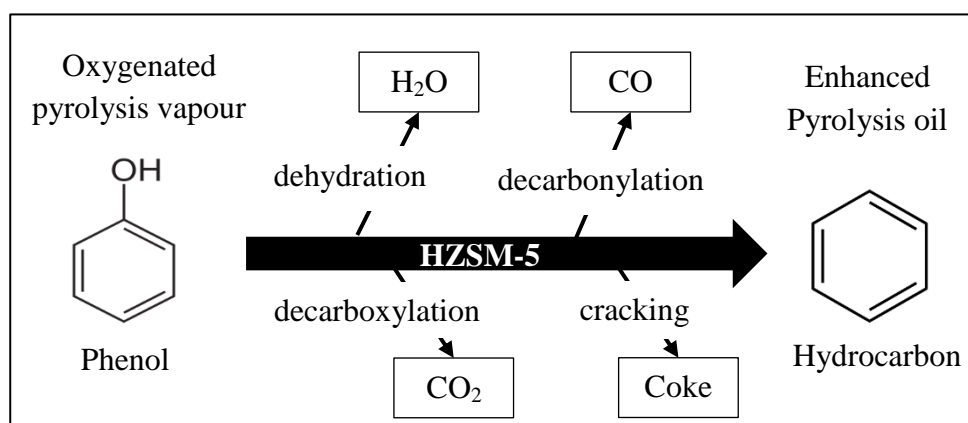


**Figure 1.2** Annual energy production rates in Malaysia (Chen, 2012)

Biomass resources in Malaysia can be categorized into three major sources such as agricultural waste, forest residues, and municipal solid waste (Mekhilef *et al.*, 2011). However, the main sources of biomass are from agricultural waste such as oil palm fronds, oil palm trunks, coconut husk, and sugarcane bagasse (Shafie *et al.*, 2012). The conversion of biomass into renewable fuel energy can be performed via various thermochemical technologies such as combustion, gasification, and pyrolysis (Kantarelis *et al.*, 2014). Among the conversion routes, pyrolysis process is considered as the most promising method to generate higher liquid oil yields in the range of 50 – 75 wt.% which depending on the type of biomass and pyrolysis operating conditions (Momayez *et al.*, 2015). Notably, pyrolysis process is defined as the thermochemical decomposition of biomass in the absence of oxygen at moderate temperatures (400 – 600 °C) (Jahirul *et al.*, 2012). In detail, the decomposition of biomass releases products in the form of volatile compounds and solid char. The volatile compounds are then condensed into pyrolysis oil, while non-condensable gaseous are collected as permanent gases (CO, CO<sub>2</sub>, H<sub>2</sub>, and CH<sub>4</sub>).

Consequently, pyrolysis oil from pyrolysis of biomass consists of highly oxygenated compounds such as ketones, phenols, and aldehydes including a low fraction of hydrocarbons. This is mainly due to the nature of biomass structure that has high oxygen elements. Moreover, during pyrolysis, the heat propagates into biomass structure and starts to degrade the lignocellulosic components (hemicellulose, cellulose, and lignin) in biomass. Other than that, the thermal degradation of each component in biomass is at a different temperature range that depends on the complex structure of components. Therefore, pyrolysis process is only beneficial on breaking the complex structure (lignocellulosic) into a simpler form of chemical compounds such as furans. Meanwhile, the possibility of converting oxygen-rich compounds into hydrocarbons in pyrolysis oil is still very low. Most scholars report that the catalytic pyrolysis is the solution to enhance the oxygenated compounds into hydrocarbons in pyrolysis oil (Galadima and Muraza, 2015; Rezaei *et al.*, 2014; Zhang *et al.*, 2013a).

Recently the catalytic pyrolysis has received much attention as most promising catalytic upgrading method of oxygenated pyrolysis vapours from biomass pyrolysis into hydrocarbons. This is due to advantages of catalytic pyrolysis such as operating at atmospheric pressure (1 atm) and considered as a cost-effective system (Kan *et al.*, 2016). Generally, catalyst and biomass are feed together into a single reactor labelled as in-situ catalytic pyrolysis system (Montoya *et al.*, 2015). Then, the generated oxygenated vapours are enhanced into hydrocarbons before entering condensation system. Meanwhile, another system is known as ex-situ catalytic pyrolysis, in which the catalyst is placed separately in secondary reactor, whereas biomass is in the first reactor (Resende, 2016). Compared to the ex-situ method, the in-situ likely reduces the capital and operating costs (Dickerson and Soria, 2013). The in-situ method has high efficiency on conversion of oxygenates into hydrocarbons in pyrolysis oil due to an immediate contact of volatile compounds at active acid sites of catalyst (Jahirul *et al.*, 2012). Besides, the heterogeneous catalyst could be easily separated from the reaction process. Moreover, oxygen element in oxygenated compounds are removed through series of reactions such as dehydration ( $\text{H}_2\text{O}$ ), decarboxylation ( $\text{CO}_2$ ), and decarbonylation ( $\text{CO}$ ) as shown in Figure 1.3 (Veses *et al.*, 2015). Finally, fewer oxygenates are left with a tremendously higher selectivity of hydrocarbons in pyrolysis oil.



**Figure 1.3** Upgrading mechanism of biomass derived oxygenated pyrolysis vapours into hydrocarbons via catalytic pyrolysis (Veses *et al.*, 2015)

Currently, the incorporation of metals into Hydrogen exchanged Zeolite Socony Mobil Five (HZSM-5) catalyst has been successfully synthesized for catalytic of oxygenated pyrolysis vapours. The incorporated metals could be either from a group of alkali earth metals, alkaline earth metals, transition metals, and rare earth metals. In general, HZSM-5 catalyst alone contains some special properties such as balanced acid sites and good textural properties. Meanwhile, metals are added into the HZSM-5 framework to prevent rapid deactivation of catalyst (coking) and simultaneously extend its lifetime during pyrolysis of biomass. For this reason, the catalytic of oxygenated pyrolysis vapours could be enhanced by incorporating metal on the HZSM-5 framework. In conclusion, biomass is a renewable energy resource which has tremendous advantages over economic, political, and social compared to conventional petroleum fuels and other renewable energy resources. Meanwhile, the utilisation of sustainable biomass via catalytic pyrolysis is the most promising technique used to enhance the biomass-derived oxygenated pyrolysis vapour. It is because catalytic pyrolysis of biomass could directly increase the  $C_6 - C_8$  hydrocarbon contents in pyrolysis oil that has wide applications. On the other hand, the dependence of  $C_6 - C_8$  hydrocarbons from petroleum fractions could be reduced with biomass as alternative feedstock. Finally, the catalytic pyrolysis requires the development and application of novel catalysts that are capable of both catalytic cracking and coke reduction.

## 1.2 Problem Statement

Global warming and limitations of fossil fuels reserved have forced the exploration biomass as new sources of renewable energy. For example, combustion of fossil fuel releases greenhouse gases ( $CO$ ,  $CO_2$ ,  $H_2$ , and  $CH_4$ ) that contribute to rising in global warming. The emissions of greenhouse gases are expected to increase from 43 million tons in 2005 to 110 million tons by 2020 (Shafie *et al.*, 2012). Meanwhile, Malaysia is gifted with abundant supplies of biomass resources that mainly come from agricultural wastes such as oil palm fronds, sugarcane



bagasse, coconut husk, and rice husk that increases annually. However, it was reported that only 10 % of the total biomass is utilised as boiler fuels to generate steam and electricity for the internal energy of agricultural mill, while 90 % of biomass is discarded as wastes and finally proceed for landfilling (Awalludin *et al.*, 2015).

Alternatively, renewable fuel energy ( $C_6 - C_8$  hydrocarbons) could be produced from the conversion of biomass through pyrolysis process (Zhang *et al.*, 2013a). However, the biomass-derived pyrolysis oil contains low yields of hydrocarbons ( $\leq 1$  %) due to the presence of oxygen-rich compounds ( $\leq 97$  wt.%) such as acids, alcohols, furans, ester, ether, ketones, phenols, sugars, and aldehydes in pyrolysis oil (Rezaei *et al.*, 2014). Besides that, the raw pyrolysis oil has some promising properties, such as less toxicity, good lubricity, and greater biodegradation than the conventional petroleum fuels (Zhang *et al.*, 2013a). Hence, biomass-derived oxygenated pyrolysis vapours should be enhanced into  $C_6 - C_8$  hydrocarbons via catalytic pyrolysis process. The HZSM-5 is widely preferred to be used as solid acid catalysts in the catalytic pyrolysis to enhance the biomass-derived oxygenated pyrolysis vapours into hydrocarbons (Rahimi and Karimzadeh, 2011).

However, the catalytic pyrolysis of oxygenated pyrolysis vapours over HZSM-5 catalyst has several shortcomings, such as low organic liquid yield, low selectivity, short lifetime, and higher coke formation that deactivate the catalyst (Zhang *et al.*, 2013a). The formation of coke is the results of the production of heavy compounds that changes the catalytic activity of the catalyst in pyrolysis process (Botas *et al.*, 2012). Therefore, the goal of this research is to extensively study the in-situ catalytic of oxygenated pyrolysis vapours from sugarcane bagasse into enhanced  $C_6 - C_8$  hydrocarbons in pyrolysis oil over the newly developed metal modified HZSM-5 catalyst, with the main aim to increase the  $C_6 - C_8$  hydrocarbons in pyrolysis oil.

### 1.3 Research Objectives

The main objective of this research is to investigate the in-situ catalytic of oxygenated pyrolysis vapours from sugarcane bagasse into enhanced  $C_6 - C_8$  hydrocarbons in pyrolysis oil using fixed-bed reactor. The specific objectives of this research are:

- i. to synthesize and characterize the Nickel-Cerium/HZSM-5 catalysts for the in-situ catalytic of oxygenated pyrolysis vapours from sugarcane bagasse into enhanced  $C_6 - C_8$  hydrocarbons in pyrolysis oil. In addition, the sugarcane bagasse as pyrolysis feedstock is also characterized.
- ii. to investigate the performance of Nickel-Cerium/HZSM-5 catalysts in catalytic of oxygenated pyrolysis vapours from sugarcane bagasse into enhanced  $C_6 - C_8$  hydrocarbons in pyrolysis oil.
- iii. to optimize process parameters of catalytic of oxygenated pyrolysis vapours from sugarcane bagasse into enhanced  $C_6 - C_8$  hydrocarbons in pyrolysis oil via response surface methodology (RSM).
- iv. to perform kinetic analysis of catalytic of oxygenated pyrolysis vapours from sugarcane bagasse into enhanced  $C_6 - C_8$  hydrocarbons over selected Nickel-Cerium/HZSM-5 catalyst.

## 1.4 Scope of Research

In order to achieve the objectives of this research, the following scopes have been identified:

- i. Synthesis of Nickel-Cerium/HZSM-5 catalysts at various nickel to cerium mass loading ratio (1:5, 2:4, 3:3, 4:2, and 5:1) on HZSM-5 via incipient wetness impregnation (IWI) method. Characterization of Nickel-Cerium/HZSM-5 catalysts via x-ray diffraction (XRD), field emission scanning electron microscopy-energy dispersive x-ray (FESEM-EDX), Brunauer Emmett Teller (BET), Fourier transform infrared (FTIR), temperature programmed desorption of ammonia (TPD-NH<sub>3</sub>), and temperature-programmed oxidation (TPO). Then, the characterization of sugarcane bagasse such as proximate analysis, elemental analysis, and calorific value via thermogravimetric analyser (TGA), elemental analyser, and bomb calorimeter respectively.
- ii. Screening and testing the catalytic performance of Nickel-Cerium/HZSM-5 catalysts on catalytic of oxygenated pyrolysis vapours from sugarcane bagasse into enhanced C<sub>6</sub> – C<sub>8</sub> hydrocarbons in pyrolysis oil at pyrolysis reaction temperatures (400, 450, 500, 550, and 600 °C), catalyst to biomass mass ratio (0.5:1.0, 1.0:1.0, 1.5:1.0, 2.0:1.0, 2.5:1.0, and 3.0:1.0), and nickel to cerium mass loading ratio (1:5, 2:4, 3:3, 4:2, and 5:1) on HZSM-5 via in-situ fixed bed reactor.
- iii. Determination of optimum value of process parameters for catalytic of oxygenated pyrolysis vapours from sugarcane bagasse into enhanced C<sub>6</sub> – C<sub>8</sub> hydrocarbons in pyrolysis oil over selected Nickel-Cerium/HZSM-5 catalyst via Box-Behnken design (BBD) in response surface methodology (RSM). Three process parameters were investigated in the optimization such as pyrolysis reaction temperatures, catalyst to biomass mass ratio, and nickel to cerium mass loading ratio on HZSM-5.

- v. Determination of kinetic parameters such as activation energy and pre-exponential factor for catalytic of oxygenated pyrolysis vapours from sugarcane bagasse into enhanced  $C_6 - C_8$  hydrocarbons in pyrolysis oil over selected Nickel-Cerium/HZSM-5 catalyst using Coats-Redfern (CR) and Flynn-Wall-Ozawa (FWO) methods.

## 1.5 Research Significance

This research utilised Nickel-Cerium/HZSM-5 catalyst as benign catalyst for enhanced hydrocarbons ( $C_6 - C_8$ ) production in pyrolysis oil via in-situ catalytic pyrolysis reaction. The addition of nickel (transition metal) and cerium (rare earth metal) into HZSM-5 framework can enhance the oxygenated pyrolysis vapours into  $C_6 - C_8$  hydrocarbons as renewable chemicals in pyrolysis oil and remarkably reduce the undesired formation of coke materials that could prolong the lifetime of the catalyst. The process variables at optimum conditions can be used to conduct the process more efficiently and to enable excellent utilisation of biomass, specifically for larger scale processes. Furthermore, the kinetic parameters obtained should be able to describe the reaction mechanisms of in-situ catalytic pyrolysis of biomass under the influence of pyrolysis reaction temperature, catalyst to biomass mass ratio, and nickel to cerium mass ratio. In addition, the  $C_6 - C_8$  hydrocarbons in pyrolysis oil can be used as combustion fuel for power generation, as feedstock for high value-added chemical production, transportation fuel, and gasoline enhancers in the petrochemical industry. The results disclosed the potential of this study to be implemented in biomass conversion to  $C_6 - C_8$  hydrocarbons under mild process conditions. Hence, the  $C_6 - C_8$  hydrocarbons from the in-situ catalytic pyrolysis reaction of biomass over Nickel-Cerium/HZSM-5 catalyst can gradually replace the conventional petroleum feedstock and improve the waste management of biomass.

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