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Catalysts to Produce Biofuels from Palm Oil-based Feedstock in Jambi Province: A Review of Performance and Potential

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Abstract :
Palm oil is a crucial agricultural commodity in Jambi Province. It holds significant promise for biofuel production, but the use of catalysts is essential for improving the process's efficiency. This study extensively assesses various catalysts' performance and potential in the context of biofuel production from palm oil-based feedstock in Jambi Province. It examines different catalysts, evaluating their effectiveness in terms of yield, selectivity, while also addressing challenges/opportunities for their development and commercialization in the region. The review of existing research underscores the diversity of catalysts explored for palm oil-based biofuel production in Jambi Province. The findings emphasize that catalysts can substantially enhance both yield and selectivity in the biofuel production process. However, there's a pressing need for further research to create more efficient and cost-effective catalysts for sustainable biofuel production. The study's prospective contribution is as a valuable resource for researchers and developers, aiding future research and development efforts and accelerating the commercialization of improved catalysts for sustainable biofuel production in Jambi Province.

Keywords: *Catalytic Cracking, Pyrolysis, Heterogeneous catalysts, Biofuels, Palm oil*

1. Introduction

The rapid expansion of the global population, coupled with improved living standards, has spurred an unprecedented surge in energy consumption. This trend is reflected in the escalating Total Primary Energy Consumed (TPEC), which exceeded 150,000,000 GW h in 2015, and is projected to soar by a staggering 57% by 2050. At the core of this demand lies the transportation sector, a vital component of the world economy, heavily reliant on non-renewable fossil fuels. Remarkably, 80% of total primary energy consumption stems from petroleum resources, with a notable 54% originating from the transportation sector. A yearly growth rate of 1.1% is anticipated for energy consumption in transportation, exacerbating the ecological imbalance, greenhouse gas emissions, and depletion of fossil fuel reserves that have become the hallmark of this unsustainable trajectory (Changmai et al., 2020).

In response to the adverse ramifications associated with fossil fuel overconsumption and its finite nature, the scientific community has fervently pursued alternative energy solutions. A promising candidate is biofuel, heralded for its renewable nature and capacity to serve as a viable substitute for traditional fossil fuels. Derived from sources such as plants, agricultural crops, municipal waste, and forestry by-products, biofuels, like biodiesel, have garnered substantial attention for their environmentally friendly attributes. Biodiesel, in particular, has exhibited qualities comparable to conventional fossil fuels, while also boasting advantages such as superior combustion efficiency, a higher flash point, elevated cetane numbers, reduced CO_2 emissions, lower sulfur content, and improved lubrication (Changmai et al., 2020).

The escalating global energy demand driven by population growth and heightened living standards has underscored the urgency of transitioning from non-renewable fossil fuels to sustainable alternatives. Among these alternatives, biofuels, with biodiesel at the forefront, exhibit the potential to mitigate the ecological and economic challenges posed by overreliance on fossil fuels. The continued exploration and development of

biofuel technologies hold the promise of a greener and more sustainable energy future for our planet (Changmai et al., 2020). This research aims to identify catalyst types investigated for biofuel production from palm oil-based feedstock in Jambi Province, to assess their performance and potential and to offer a comprehensive overview of catalyst development in this context.

2. Types of Biofuel Production Process

Indonesia's vast expanse of oil palm plantations, covering 14.68 million hectares by 2019, positions the nation as a key player in the palm oil sector. This agricultural growth has propelled palm oil mills to the forefront, generating an impressive 27,898,875 tons of Crude Palm Oil (CPO) (BPS, 2021). Within this burgeoning industry lies an untapped opportunity to harness the potential of palm oil through innovative biofuel production methods.

The inherent hydrocarbon chains within crude palm oil offer a promising avenue for transformation. The process of cracking, capable of breaking down these lengthy hydrocarbon chains, holds the potential to usher in a new era of biofuel creation. Among the various biofuels derived from palm oil, biodiesel stands out. This particular biofuel is characterized as mono alkyl-ester chains of fatty acids from both animal and vegetable origins, providing a renewable, non-toxic, and biodegradable alternative (Sirajudin et al., 2013).

Various approaches exist for converting vegetable oil into biofuels, encompassing transesterification, pyrolysis, hydrocracking, hydrothermal treatment, and catalytic cracking. Transesterification, although commonly used, produces biodiesel with compromised stability and higher costs compared to petroleum-based options (Mancio et al., 2016). On the other hand, catalytic cracking emerges as a cost-effective strategy for transforming vegetable oils into biofuels akin to petroleum-based counterparts. This intricate process involves removing oxygen atoms through complex chemical reactions, resulting in heightened cost-efficiency and improved product yields.

The art of cracking involves two distinct methods: thermal cracking and catalytic cracking. The former involves applying heat to disintegrate long hydrocarbon chains, albeit at the cost of high energy consumption (Li et al., 2016). In contrast, catalytic cracking employs catalysts to facilitate controlled chain breakdown, offering a more efficient approach (Roesyadi et al., 2013).

In the realm of biofuels, the term encompasses both gaseous and liquid fuels derived from biomass, extensively used in transportation (Demirbas, 2008). Biodiesel production encompasses various techniques, including trans-esterification and catalytic cracking. While trans-esterification prevails due to its technical simplicity and efficiency, it generates substantial glycerol byproducts necessitating costly extraction processes . On the other hand, catalytic cracking not only yields biodiesel but also valuable gasoline and kerosene outputs, presenting a multi-pronged solution . This method's cost-effectiveness, high conversion rates, and versatility make it a compelling choice, especially for repurposing waste materials (Arita et al., 2020a).

The concept of catalytic cracking aligns with thermal cracking but introduces catalysts that remain unaffected throughout the process, thereby enhancing overall efficiency. Widely applicable across diverse feedstocks, catalytic cracking thrives within refinery settings, contributing to improved processes and a diversified product range. Operating at temperatures ranging from 485 to 540 °C (900–1000 °F) and pressures up to 100 psi, catalytic cracking becomes a cornerstone of efficient biofuel production [27].

Incorporating catalytic cracking into Indonesia's palm oil industry holds the potential to not only boost biofuel production but also address waste management. This innovative approach can reshape the nation's energy landscape, emphasizing sustainability, economic viability, and environmental responsibility. As Indonesia harnesses its palm oil potential through catalytic cracking, a new era of biofuel innovation dawns, contributing to a greener and more sustainable future.

3. Investigated Catalysts of Biofuel Production in Jambi Province

Activated carbon/charcoal is widely used in catalytic cracking due to its strong adsorption capacity and stability under varying pH conditions. Palm oil shell-derived activated carbon provides benefits such as low ash content, reactivity, and ample pore size [11]. Common methods for catalyst preparation include precipitation, impregnation, ion exchange, adsorption, and deposition-precipitation. This review focuses on Nickel, Chromium, and Cobalt solutions for activated carbon catalysts. Nickel acts as an economical, selective catalyst carrier, evenly distributed within carrier pores to improve surface area, stability, and

resistance to sintering (Zhang et al., 2021). With a planar crystal structure, nickel catalyzes C-C and C-H bond cleavage. Chromium, utilized as a catalyst, achieves extensive active surface coverage by dispersing components within the carrier. Cobalt, a transition metal, excels as a catalyst in hydrogenation due to its incomplete electron configuration, although its use in catalytic cracking is restricted (Prabasari et al., 2019). Incorporating active metals on activated carbon improves catalyst selectivity [14].

Prabasari et al. (2022) focus on catalytic cracking of Crude Palm Oil (CPO) using a Ni-carbon catalyst prepared through ion exchange, aiming to optimize conversion efficiency. By systematically varying Ni-metal concentrations (1%, 2%, and 3%) and reaction temperatures (450℃, 500℃, and 550℃), the study investigates the influence of these parameters on the process. Characterization via X-ray Diffraction (XRD) and Scanning Electron Microscopy with Energy Dispersive X-ray (SEM-EDX) confirms successful incorporation of nickel metal into the carbon catalyst. Significantly, the highest conversion rate of 74.14% is achieved at 450℃ and 2% Ni-carbon concentration, surpassing thermal and pure catalyst catalytic cracking. The resulting liquid products exhibit densities in the range of fuel oil and diesel, indicating their potential as biofuels. This study provides crucial insights into catalyst design and process conditions, contributing to the development of efficient and sustainable biofuel production methods (Prabasari et al., 2022).

Nazarudin et al. (2022) conducted a study on converting used cooking oil-derived methyl ester into biofuel through catalytic cracking, employing Ni-impregnated activated charcoal catalysts. The research highlights the pressing need for renewable energy sources and investigates catalytic cracking as a potential solution. The methodology involves preparing activated charcoal catalysts derived from oil palm shells and impregnating them with nickel solutions of varying concentrations. SEM-EDX analysis validates successful nickel integration into the charcoal matrix, with the highest content achieved through 2% nickel solution impregnation. Systematic experimentation identifies optimal conditions for biofuel production, revealing that catalytic cracking of methyl esters with Ni-impregnated activated charcoal catalyst at 3% Ni (NO3)2.9H2O and 400℃ yields an impressive 65.58% liquid fraction, surpassing the calorific content of commercial Biodiesel (B20). This research addresses energy challenges and contributes to sustainable energy discourse by offering a viable biofuel alternative (Nazarudin et al., 2022).

Nazarudin et al. (2020) make a significant contribution to alternative fuel production by investigating the catalytic conversion of used cooking oil into biofuel. The research focuses on the development and optimization of Cr-charcoal catalysts. These catalysts, prepared by impregnating varying concentrations of chromium solutions (1%, 2%, and 3%) into charcoal derived from palm oil industry waste, display amorphous structures and confirmed chromium impregnation through XRD patterns and SEM images. Importantly, the study reveals that the highest yield of liquid oil fraction, a key indicator of biofuel production efficiency, is achieved at 500℃ using a 3% Cr-charcoal catalyst. Moreover, the analysis of the liquid product underscores its potential as a substitute for conventional diesel fuels, with 86.35% of the product consisting of diesel oil with carbon atoms ranging from C8 to C24. Beyond technological advancements, the research aligns with sustainability goals by repurposing waste materials for catalyst support, reflecting circular economy principles. This study encapsulates catalyst preparation, process optimization, and product analysis in the realm of biofuel production, contributing to renewable energy alternatives and waste utilization (Nazarudin et al., 2020).

Nazarudin et al. (2019) focus on converting used cooking oil into biofuel through catalytic cracking using Cr-charcoal catalysts. These catalysts, synthesized through ion-exchange modification, exhibit enhanced catalytic activity due to increased active sites on their surfaces. The study explores different chromium concentrations for ion-exchange and temperatures for catalytic cracking. Optimal conditions yielding the highest oil fraction are achieved at 450℃, using a 1% Cr solution-synthesized Cr-charcoal catalyst, primarily producing diesel oil (C8–C20) with an area percentage of 80.67%. The findings underscore the impact of catalyst composition and temperature on product yields, presenting a significant advancement in sustainable waste-to-biofuel conversion strategies (Nazarudin et al., 2019).

Prabasari et al. (2019) investigate the potential of cobalt-impregnated carbon catalysts (Co-carbon) to enhance the cracking process and biofuel yields. Through systematic experimentation, the study examines the effect of cobalt concentrations (1%, 2%, and 3%) on carbon catalysts and characterizes their structure using techniques like X-ray diffraction and SEM. Catalytic cracking experiments cover a temperature range of 450℃ to 550℃. Notably, at 500℃, using a 1% Co-carbon catalyst leads to the highest liquid oil fraction and a lower activation energy, indicating efficient cracking. A 3% Co-carbon catalyst results in the highest

yield of diesel oil (C12–C18) in the product. The research also contrasts these findings with thermal cracking, revealing that the highest biofuel conversion (53.34%) occurs at 550°C. Prabasari's study emphasizes the significance of temperature and cobalt concentration in determining biofuel yield and composition, providing insights into tailored biofuel production from waste materials (Prabasari et al., 2019). Nazarudin et al. (2018) investigate the impact of temperature during activated carbon production on its catalytic performance in the cracking of crude palm oil (CPO) to fuel. Using palm shell waste, the study examines two different production temperatures (450℃ and 550℃) for active carbon catalysts. The active carbon catalyst significantly enhances liquid conversions by 85% in the catalytic cracking of CPO compared to non-catalytic cracking. Higher production temperatures improve liquid conversion during catalysis. This research underscores the potential of palm oil mill waste for sustainable catalyst production, aligning with waste-to-value principles. The comparison with thermal cracking highlights the superior performance of active carbon catalysis in both gas and liquid conversion. Nazarudin's study provides insights into temperature-controlled active carbon catalysts from palm shell waste, contributing to efficient and sustainable catalytic conversion processes (Nazarudin et al., 2018).

Zeolites play a vital role in catalytic cracking for chemicals and oil refining in the petrochemical sector. Their high surface areas and adsorption capacities result from molecular-sized pores (Corma, 2003). Prominent zeolites like H-ZSM-5, H-Beta, and H-USY are commonly used for upgrading processes (Chaihad et al., 2018). Zeolite efficiency as a cracking catalyst depends on acidity and stability, linked to Si/Al ratio. Higher acidity enhances catalytic activity, thermal stability, and acid resistance. The active Bronsted-acid core for cracking contains Al atoms (Park et al., 2017). Y-zeolites exhibit excellent temperature stability (Elordi et al., 2011). ZSM-5 displays moderate hydrocarbon selectivity, with medium-pore ZSM-5 converting n-alkanes into aromatics and selectively cracking low octane components into higher octane ones. Spent FCC catalysts effectively catalyze pyrolysis of polymers due to retained acidity, although with lower activity compared to fresh FCC catalysts. The FCC catalyst contains zeolite-Y crystals dispersed in a silica-alumina-clay matrix. Zeolite-Y's extensive surface area and pore volume, often underutilized, offer potential (Arita et al., 2020a).

Rosmawati et al. (2019) explore the effectiveness of the H-USY catalyst in waste cooking oil catalytic cracking. The experiment investigates various conditions, including reaction temperatures (400-550°C) and times (30-60 minutes), while maintaining a waste cooking oil to catalyst ratio of 40:1. Notably, optimal conditions of 450 ℃ for 45 minutes yield the highest liquid biofuel production at 60.98%, with the biofuel composition containing 28.02% diesel products (C17-C20), 23.96% gasoline (C6-C12), and 7.78% heavy oil (C20 >). This study highlights the importance of catalyst selection and optimized conditions in converting waste to biofuel, offering insights into sustainable energy generation and waste management (Rosmawati et al., 2019).

The study by Nazarudin et al. (2020) addresses the urgent need for sustainable plastic waste management and alternative fuel production through catalytic cracking. Investigating the conversion of Polyethylene Terephthalate (PET) plastic waste and palm fiber waste into Oil Liquid Product (OLP) using Ni-USY zeolite catalysts, the research synthesizes catalysts with varying Ni-metal concentrations and characterizes their crystalline FAU framework through SEM and EDX analysis. The experimental investigation delves into the impact of reaction conditions on OLP production, revealing the highest OLP percentage (24.5%) achieved at 450℃ for 10 minutes using a Ni-USY catalyst prepared with 2% Nickel Nitrate solution. This study's contribution lies in its optimized catalyst synthesis, exploration of reaction parameters, and successful demonstration of plastic waste and palm fiber waste conversion into valuable liquid fuel. It aligns with sustainability goals, offering a significant advancement in waste-to-fuel technology (Nazarudin et al., 2020).

The study by Arita et al. (2020a) investigates the catalytic cracking of waste cooking oil for biofuel production using a combined H-USY and ZSM-5 catalyst system. The research examines the influence of operating conditions, including reaction temperatures (400℃ to 550℃) and reaction times (30 to 60 minutes), on the yield and composition of the produced biofuel. Optimal conditions for the process are identified as 450 ℃ reaction temperature and 60 minutes reaction time, resulting in a substantial 49.35% mass yield of liquid biofuel with specific compositions of gasoline (15.71%), diesel products (11.97%), and heavy oil (1.09%). The study also reports physical properties of the biofuel, including a calorific value of 40.0906 MJ/kg, density of 9.069 g/cm3, and kinematic viscosity of 9.2441 cSt. Arita's work emphasizes the

interplay between catalyst selection, operating conditions, and resultant biofuel properties, offering insights into the potential of catalytic cracking for transforming waste cooking oil into a sustainable biofuel resource (Arita et al., 2020a).

The dwindling fossil crude reserves necessitate a shift to renewable energy sources, prompting attention towards biodiesel as an alternative. Innovative solutions are sought to enhance biodiesel quality, such as catalytic cracking using Ni-ZSM-5 catalysts. Alfernando et al. (2019) pioneers this approach, investigating the catalytic cracking of biodiesel under various conditions. Ni-ZSM-5 catalysts are synthesized through ion-exchange, with different Ni-metal concentrations (1%, 2%, and 3%) and subjected to catalytic cracking at varying temperatures (450°C, 500°C, and 550°C). Characterization techniques confirm successful Ni adsorption onto the catalyst, with optimal results observed in 1% Ni catalysts at 450°C, yielding a significant diesel oil fraction (C13–C19) covering 92.96% of the chromatogram peak area. The research underscores the viability of catalytic cracking for improving biodiesel quality, positioning it as a renewable fuel source for sustainable energy (Alfernando et al., 2019). Further research may explore scaling up the process and investigating catalyst regeneration mechanisms to facilitate practical implementation.

The study by Arita et al. (2020b) contributes valuable insights by optimizing bio-oil generation from empty fruit bunches. The research systematically explores effective weight ratio combinations of ZSM-5 and spent fluid catalytic cracking (FCC) catalysts. The investigation involves varying catalyst ratios (10:90, 20:80, 30:70, 40:60, and 50:50) and conducting pyrolysis at 400ºC and 500ºC, with a constant empty fruit bunches to catalysts weight ratio of 10:1. The results highlight key combinations, 10:90 and 50:50, at 500ºC, yielding the highest bio-oil percentages of 48.88% and 47.49%, respectively. Furthermore, the study explores the composition and characteristics of the bio-oil produced. Notably, the 50:50 combination at 500ºC exhibits significant selectivity towards phenolic compounds, with a peak area of 59.85%. This is pivotal, as phenolic compounds hold value in bio-oil. The bio-oil samples demonstrate favorable properties, including a heating value of 26.94 MJ/kg and an average density of 1.03 g/cm³. Arita's research advances the refinement of bio-oil production processes, promoting the sustainable use of biomass for renewable energy (Arita et al., 2020b).

Silica (SiO2) serves as a catalyst support with notable Lewis acidity (Nazarudin et al., 2017). It can be derived from palm kernel shell ash, containing a high silica content of 67.03%, a byproduct of palm oil industry's boiler activity (Firdaus, 2012). This makes silica from palm kernel shell ash a potential substitute for zeolite as a catalyst support. Building upon prior research, the production of Cr/SiO2 catalyst could be explored to enhance catalytic cracking of CPO (Crude Palm Oil).

In Nazarudin et al. (2017) study, the synthesis and application of Cr/SiO2 catalyst from waste palm oil factory charcoal for catalytic cracking of Crude Palm Oil (CPO) were investigated. The research aimed to characterize the catalyst and evaluate its catalytic activity. Through laboratory experiments, the synthesized Cr/SiO2 catalyst was analyzed using X-ray Diffraction (XRD) and Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS). The catalyst exhibited a unique composition with a Hexagonal Crystal System for SiO_2 and an Orthorhombic Crystal System for Cr/SiO_2. In the catalytic cracking of CPO, the Cr/SiO_2 catalyst demonstrated significant activity, with conversion percentages of Catalytic Cracking Products (CHP) ranging from 58.53% to 74.08% for different catalyst:CPO ratios. However, challenges in achieving high selectivity and conversion rates were evident, emphasizing the need for further optimization. Importantly, the use of waste palm oil factory charcoal as a silica source for catalyst synthesis highlights potential sustainable waste management practices, with broader implications for resource utilization and environmental conservation. The study underscores the significance of catalyst characterization, catalytic activity evaluation, and waste-to-resource approaches in advancing catalytic processes (Nazarudin et al., 2017).

Table 1 below summarizes the investigated catalysts usage in biofuel production which are conducted and utilized natural resources in Jambi Province.

Table 1. Investigated catalysts of biofuel production in Jambi Province

No	Catalyst	Palm Oil-based Biomass Feedstock	Optimum Conditions (ratio catalyst:feedstock, temperature in ºC, time in minute)	Conversion (C) and/or Yield (Y)	Biofuel Analysis	Reference
1	Ni-Carbon Ion Exchanged Method (2% Ni solution)	CPO*	1:10, 450, 120	C=74.14% Y=80.67%	Biogasoline and biodiesel	Prabasari et. al, 2022
2	Ni-Charcoal Impregnation Method(3% Ni solution)	Methyl Ester from UCO*	1:30, 400, 100	Y=65.58%	Mainly biodiesel	Nazarudin et al., 2022
3	Cr-Charcoal Impregnation Method (3% Cr solution)	UCO	1:10, 500, 60	Y=34.59%	Mainly biodiesel	Nazarudin et al., 2019
4	Cr- Charcoal Ion Exchange Method (1% Cr solution)	UCO	1:23 , 450, 75	Y=45.22%	Mainly biodiesel	Nazarudin et al., 2019
5	Co-Carbon Impregnation Method (1% Co solution)	UCO	1:20 , 550, 60	Y=32.65%	Mainly biodiesel	Prabasari et. al, 2019
6	Activated Carbon	CPO	1:10, 550, 60	C=85%	Biogasoline and biodiesel	Nazarudin et al., 2018
7	Combined H-USY and ZSM-5 (ratio 1:1)	WCO*	1:40, 450, 60	Y=49.35 %	Biogasoline and biodiesel	Arita et al., 2020
8	Ni-USY (2% Ni Solution)	Mixture of palm fibre and waste PET* (ratio 3:1)	1:6 , 450, 10	Y=24,5%	Mainly bio-oil	Nazarudin et al., 2019
9	H-USY	WCO	1:40 , 450, 45	Y=60.98%	Mainly biodiesel	Rosmawati et al., 2019
10	Combined ZSM-5 and Spent FCC (ratio 10:90)	EFB*	1:10, 500, 60	Y=48.88 %	Mainly bio-oil	Arita et al., 2020
11	Ni-ZSM-5 Ion Exchange Method (2% Ni Solution)	Methyl Ester from UCO	1:32, 450, 100	Y=77.91%	Mainly biodiesel	Alfernando et al., 2019
12	Cr-SiO_2 (3% Cr)	CPO	1:30, 450, 60	Y=36%	Mainly bio-oil	Nazarudin et al., 2017

*Term meaning: CPO (Crude Palm Oil); UCO (Used Cooking Oil); WCO (Waste Cooking Oil); EFB (Empty Fruit Bunch); PET (Polyethylene Terephthalate)

Conclusion

In summary, this review emphasizes the crucial role of activated carbon/charcoal catalysts and zeolites like ZSM-5, H-USY, and Spent FCC improve catalytic cracking and showcasing acidity and stability importance, particularly Nickel, Chromium, and Cobalt solutions, in catalytic cracking. Various studies

highlight how catalyst composition, concentration, temperature, and reaction conditions impact biofuel production efficiency and selectivity. Nickel excels in C-C and C-H bond cleavage, Chromium enhances surface coverage, and Cobalt shows promise in hydrogenation. Using waste materials like palm oil shells and used cooking oil aligns with sustainability goals. These findings advance catalyst synthesis, process conditions, and waste-to-biofuel conversion. The research addresses renewable energy demand and waste management, driving greener catalytic cracking. Further research is vital for practical implementation and refining these biofuel production methods.

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