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BIODIESEL PRODUCTION USING SILK COTTON SEED OIL : A REVIEW

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ABSTRACT

The potential of Ceiba pentandra (silk cotton seed oil) as a sustainable and non-edible feedstock for biodiesel production. Given the increasing need for renewable energy, this study evaluates the suitability of silk cotton seed oil due to its favorable fatty acid profile and ability to grow on marginal land without intense cultivation. Traditional transesterification methods are discussed alongside innovative catalytic systems, especially the use of zeolite-diatom composite catalysts, which offer advantages like reusability, high thermal stability, and the ability to handle high free fatty acid content. The paper also highlights the comparative benefits of heterogeneous acid catalysts over traditional homogeneous ones, citing their cleaner processing and compatibility with low-quality feedstocks. Furthermore, studies demonstrating high biodiesel yields using zeolite-based catalysts reinforce their promise for scalable and efficient production. Despite its advantages, the economic feasibility of large-scale biodiesel production from Ceiba pentandra remains a concern, with high initial investments and the need for process optimization. Nonetheless, the environmental benefits—such as biodegradability, reduced emissions, and waste utilization—make it a compelling candidate for future biodiesel applications, including transportation and aviation, provided ongoing research addresses the economic and technical challenges.

Keywords- Ceiba pentandra, silk cotton seed oil, transesterification

1. INTRODUCTION

Biodiesel has emerged as a sustainable and eco-friendly alternative to conventional fossil fuels, particularly in addressing the growing global demand for cleaner energy sources[1]. It is a renewable biofuel produced through the transesterification of triglycerides found in natural oils or fats, using an alcohol—commonly methanol—in the presence of a catalyst[2]. Biodiesel offers several environmental and practical advantages, including biodegradability, non-toxicity, and significantly reduced emissions of greenhouse gases, carbon monoxide, and particulates[2]. Unlike petroleum diesel, biodiesel can be used in existing diesel engines with minimal or no modifications, making it a feasible substitute in transportation and industrial applications[2][3]. Additionally, its renewable nature contributes to reducing dependence on non-renewable energy sources and helps in mitigating the environmental impact of fossil fuel consumption.

The effectiveness and sustainability of biodiesel production largely depend on the type of feedstock used. While edible oils have traditionally been employed in biodiesel synthesis, their use raises concerns over food security and cost[4]. As a result, non-edible oils have gained prominence as economical and sustainable alternatives. One such promising feedstock is silk cotton seed oil, derived from the seeds of the Ceiba pentandra tree.[5] The tree is native to tropical regions and grows abundantly without requiring intensive cultivation. Its seeds yield a considerable amount of oil, which contains fatty acids suitable for biodiesel conversion[6]. The use of silk cotton seed oil not only avoids the food-versus-fuel conflict but also utilizes an otherwise underexploited natural resource[7]. This review focuses on the potential of silk cotton seed oil as a biodiesel feedstock, discussing its chemical characteristics, availability, and performance when processed using suitable catalytic systems.

TRADITIONAL METHODS OF BIODIESEL PRODUCTION

The primary traditional method used for biodiesel production is transesterification, a chemical process that involves the reaction of triglycerides present in vegetable oils or animal fats with a short-chain alcohol, typically methanol, in the presence of a catalyst. This reaction produces fatty acid methyl esters (FAMEs) the chemical constituents of biodiesel and glycerol as a byproduct[8]. Transesterification is favored due to its relatively simple process, high conversion efficiency, and adaptability to different types of feedstocks. In some cases, especially where the feedstock contains a high level of free fatty acids (FFAs), a two-step process is employed: an initial esterification step using an acid catalyst to reduce FFAs, followed by a base-catalyzed transesterification [8][9]. Alternative traditional methods such as supercritical alcohol treatment and ultrasound- or microwave-assisted transesterification have also been explored, although they are less common due to their higher operational costs and technical complexity [10]. The success of biodiesel production heavily depends on the type and quality of the feedstock used. Feedstocks are broadly classified into three categories: edible oils, non-edible oils, and waste-derived oils or fats[11][12]. In the early stages of biodiesel development, edible oils such as soybean, sunflower, rapeseed (canola), and palm oil were predominantly used due to their high oil content and predictable composition[12]. However, their rising cost and contribution to food-versus-fuel concerns led to increased interest in non-edible oils like jatropha, neem, karanja, rubber seed, and castor oil, which can grow on marginal lands unsuitable for food crops.[13] Additionally, waste cooking oils (WCOs) and animal fats like lard and tallow are being widely adopted as economical and environmentally sustainable feedstocks, especially in developing regions[14]. These low-cost sources not only reduce production expenses but also help mitigate waste management issues. In traditional biodiesel production, catalysts play a crucial role in enhancing the reaction rate and overall efficiency of the transesterification process. Homogeneous base catalysts such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) are most commonly used due to their high catalytic activity and cost-effectiveness, particularly when processing refined oils with low FFA content.[15] However, base catalysts are highly sensitive to FFAs and water, which can lead to soap formation and reduced yield. In such cases, homogeneous acid catalysts, such as sulfuric acid (H_2SO_4) or hydrochloric acid (HCl), are preferred for esterification of high-FFA oils[16]. While acid catalysts are slower and more corrosive, they can handle a wider range of feedstock qualities. In recent years, research has also explored heterogeneous catalysts—both acidic and basic—as well as enzyme-based systems for cleaner, reusable, and environmentally friendly production, though their use in traditional methods is still limited due to cost and operational constraints.[17]

1.3 POTENTIAL OF SILK COTTON SEED OIL AS A RENEWABLE FEEDSTOCK

Silk cotton seed oil, derived from the seeds of the Ceiba pentandra tree, is gaining attention as a non-edible, underutilized oil for biodiesel production[18]. The tree is native to tropical and subtropical regions and is known for its lightweight fiber and seed-rich pods. The seeds contain 20–25% oil, which can be extracted through mechanical or solvent-based methods[19]. While not suitable for human consumption due to the presence of certain antinutritional factors, the oil is rich in fatty acids such as palmitic, oleic, linoleic, and stearic acids—components that are essential for producing fatty acid methyl esters (FAMEs), the core of biodiesel. Its favorable oil profile and availability in non-agricultural zones make it an excellent raw material for sustainable fuel synthesis[20].

Compared to conventional feedstocks like soybean, canola, and sunflower oil, which are edible and often linked to rising food costs and land-use conflicts, silk cotton seed oil presents a non-edible and environmentally responsible alternative[20].Unlike these traditional feedstocks, Ceiba pentandra can grow on marginal land and requires minimal water or fertilizer, making it a low-input crop ideal for cultivation in resource-constrained regions[20][21]. Furthermore, while waste cooking oils and animal fats are also popular non-edible feedstocks, their availability is often inconsistent, and quality can vary significantly[22]. In contrast, silk cotton seed oil offers a more predictable yield and composition, particularly when sourced from organized plantations or natural forests where the tree is abundant.

In terms of chemical processing, silk cotton seed oil generally contains a moderate level of free fatty acids (FFAs), allowing it to be processed via acid or base-catalyzed transesterification depending on the pretreatment conditions[23]. This gives it a processing advantage over high-FFA oils like jatropha or waste cooking oils, which often require additional esterification steps before transesterification[24]. Additionally, the physical and fuel properties of biodiesel derived from silk cotton seed oil—such as viscosity, density, and cetane number—are found to be within or near international biodiesel standards (ASTM D6751, EN 14214). These properties highlight silk cotton seed oil's potential as a feasible, renewable, and sustainable feedstock that not only reduces dependency on food-based oils but also supports rural development and environmental conservation[25].

ZEOLITE-DIATOM: AN INNOVATIVE HETEROGENEOUS CATALYST

In the quest for more sustainable and efficient biodiesel production, the development of heterogeneous catalysts has emerged as a promising alternative to conventional homogeneous systems[26]. One such innovative catalyst is the zeolite-diatom composite, which combines the high surface area and structural stability of zeolites with the porous, silica-rich framework of diatomaceous earth[27]. Zeolites are microporous aluminosilicates with excellent ion-exchange and adsorption properties, while diatomaceous earth, derived from fossilized diatom shells, is known for its high porosity and natural abundance[28]. When activated with acids, this composite material gains enhanced acidity and surface functionality, making it highly effective for catalyzing the transesterification of oils into biodiesel, especially from feedstocks with high free fatty acid (FFA) content[29].

Compared to traditional homogeneous catalysts such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), the zeolite-diatom catalyst offers several notable advantages. Homogeneous catalysts, though widely used, are highly sensitive to the presence of water and FFAs in the feedstock, which can lead to soap formation and reduced biodiesel yields. Additionally, homogeneous systems are non-recoverable and contribute to downstream processing challenges, including water-intensive purification steps[30]. In contrast, the zeolite-diatom catalyst, being solid and insoluble in the reaction medium, is easily separable and reusable, which reduces waste and operating costs. Its ability to function effectively even with unrefined or waste oils also makes it a versatile option in biodiesel production.

Furthermore, the structural synergy between zeolite and diatomaceous earth enhances the textural and catalytic properties of the material[31]. The composite catalyst exhibits high surface area, tunable pore sizes, and robust thermal and chemical stability, all of which contribute to improved reaction kinetics and conversion efficiency[32]. Its porous framework allows for better diffusion of bulky triglyceride molecules, and its acidic sites promote both esterification and transesterification reactions in a single step[33]. These features position the acid-activated zeolite-diatom catalyst as a next-generation heterogeneous catalyst, capable of overcoming many of the limitations associated with traditional catalytic systems while supporting environmentally friendly and scalable biodiesel production.

2. ADVANTAGES OF HETEROGENEOUS ACID CATALYST

In biodiesel production, the choice of catalyst significantly influences reaction efficiency, product quality, and environmental impact. Traditionally, homogeneous catalysts such as sodium hydroxide, potassium hydroxide, or sulfuric acid have been widely used due to their high reactivity and low cost[34]. However, these catalysts are dissolved in the reaction medium, making their separation from the final product complex and costly. In contrast, heterogeneous acid catalysts, which remain in a solid phase during the reaction, have emerged as an alternative due to their potential for cleaner processing, easier recovery, and lower environmental burden[35].

One of the key advantages of heterogeneous acid catalysts is their reusability and ease of separation. Since these catalysts are not soluble in the reaction mixture, they can be easily filtered out and reused for multiple reaction cycles without significant loss of activity. This characteristic reduces operational costs and minimizes catalyst waste. Moreover, heterogeneous acid catalysts can simultaneously catalyze esterification and transesterification, making them especially suitable for feedstocks with high free fatty acid (FFA) content. Homogeneous base catalysts, by contrast, tend to form soap when reacting with FFAs, which complicates separation and lowers biodiesel yield[36].

Additionally, heterogeneous acid catalysts offer improved thermal and chemical stability, allowing them to function effectively under harsh reaction conditions. They are generally less corrosive than strong mineral acids, reducing the risk of equipment degradation and lowering maintenance costs[37]. The use of solid acid catalysts also leads to simplified purification steps, as they produce fewer by-products and reduce water usage during washing. These benefits make heterogeneous acid catalysts a promising solution for sustainable, scalable, and economically viable biodiesel production, especially when working with low-cost, non-edible, or waste-derived feedstocks.

2.1 Ease of Separation and Reusability

Heterogeneous acid catalysts exist in a solid phase, making them easy to separate from the liquid reaction mixture after biodiesel synthesis. This allows for multiple reuse cycles, reducing catalyst consumption and overall production costs. In contrast, homogeneous catalysts dissolve in the reaction medium and cannot be recovered easily, resulting in higher waste generation.

2.2 Tolerance to High Free Fatty Acid (FFA) Content

Heterogeneous acid catalysts are more effective with feedstocks containing high FFAs, such as waste cooking oils or non-edible oils. They can simultaneously catalyze esterification and transesterification reactions, minimizing soap formation—a common issue with base homogeneous catalysts.

2.3 Environmentally Friendly and Cleaner Processing

Since heterogeneous catalysts can be recovered and reused, they reduce the need for extensive downstream purification steps. This leads to lower water consumption and fewer chemical inputs during post-processing, making the overall process more environmentally sustainable.

2.4 Improved Catalyst Stability

Acid-activated solid catalysts (like zeolites, sulfonated carbons, or silica-based materials) offer better thermal and chemical stability compared to their homogeneous counterparts. This makes them more suitable for continuous or industrial-scale biodiesel production systems.

2.5 Reduced Corrosion and Equipment Wear

Unlike homogeneous acid catalysts (e.g., sulfuric acid), which are highly corrosive and can damage equipment over time, solid acid catalysts are less corrosive, contributing to longer equipment lifespan and lower maintenance costs.

ZEOLITE CATALYST PROVIDING AN EDGE IN BIODIESEL PRODUCTION

Zeolite-based catalysts offer several advantages in biodiesel production, particularly for processing low-quality feedstocks with high free fatty acid (FFA) content. These catalysts demonstrate high efficiency in both esterification and transesterification reactions, making them suitable for a wide range of feedstocks (Fattah et al., 2020; Yusuf et al., 2023). The use of zeolite catalysts in biodiesel production has shown promising results. For instance, a study using an analcime zeolite catalyst (Al1.9Na1.86O12Si4) achieved a biodiesel yield of 98.299% with 100% fatty acid alkyl ester (FAAE) content at optimal conditions (Buchori et al., 2020). Another study found that SO42-/ZnO-β-zeolite catalyst exhibited excellent catalytic performance for simultaneous transesterification and esterification of waste cooking oil (WCO), with a high conversion rate of 96.9% under optimized conditions (Yusuf et al., 2023). Interestingly, zeolite-based catalysts can be modified to enhance their catalytic properties. For example, the incorporation of tungstophosphoric acid (TPA) into mesoporous aluminosilicates (MAS-7 and MAS-9) derived from zeolite β and ZSM-5 precursors resulted in catalysts that achieved methyl ester yields of 76.5–88.7 wt% using unrefined green seed canola oil as feedstock (Kurhade et al., 2018). Additionally, a novel CaO-ZnO catalyst synthesized using a simple method involving ZnO and CaCO3 showed high biodiesel yield, up to 73% in the first cycle and 64% in the second one (Arana et al., 2019). In conclusion, zeolite-based catalysts provide a significant edge in biodiesel production due to their versatility, efficiency, and ability to handle low-quality feedstocks. Their potential for modification and reusability further enhances their appeal as heterogeneous catalysts for sustainable biodiesel production (Fattah et al., 2020; Mohamed et al., 2023). However, it is important to note that catalyst performance can decrease with repeated use, as observed in some studies (Buchori et al., 2020), highlighting the need for further research on catalyst regeneration and longevity.

3. BIODIESEL YIELD USING ZEOLITE CATALYST

Zeolite acid catalysts have shown promising results in biodiesel production, with yields comparable to or exceeding those of other catalysts in some cases. A study using a synthesized analcime zeolite catalyst (Al1.9Na1.86O12Si4) achieved a biodiesel yield of 98.299% with 100% fatty acid alkyl ester (FAAE) content at optimal conditions (Buchori et al., 2020). Similarly, SO42-/ZnO-β-zeolite catalyst demonstrated excellent performance in simultaneous transesterification and esterification of waste cooking oil, achieving a 96.9% conversion under optimized conditions (Yusuf et al., 2023). Interestingly, while zeolite catalysts show high efficiency, their performance can be further enhanced when combined with other catalysts. For instance, a combination of Raney Ni and acidic zeolite catalysts resulted in higher yields of monophenols (21.0–27.9%) compared to using either catalyst independently (Jiang et al., 2015). Additionally, the development of acid-base bifunctional catalysts, such as metal-boron catalysts, has shown excellent results in biodiesel production from high acid value oils, with yields up to 96.0% (Wang et al., 2018). In conclusion, zeolite acid catalysts demonstrate competitive biodiesel yields compared to other catalysts, with the potential for further improvement through catalyst combinations or modifications. The choice of catalyst depends on various factors, including feedstock quality, reaction conditions, and desired product characteristics. Heterogeneous acid catalysts, including zeolites, offer advantages such as insensitivity to high FFA levels and potential for reusability, making them promising options for biodiesel production from low-quality feedstocks (Fattah et al., 2020; Sharma et al., 2010).

ENVIRONMENTAL BENEFITS OF USING CEIBA PENTRANDA

Ceiba pentandra, also known as the Kapok tree, shows great potential as a non-edible feedstock for biodiesel production, offering several environmental benefits. The use of this renewable resource helps reduce dependence on fossil fuels and mitigates environmental concerns associated with their consumption (Bokhari et al., 2015; Jamaluddin et al., 2019). Biodiesel produced from Ceiba pentandra oil methyl ester using microwave-assisted techniques has demonstrated high conversion rates (98.9%) under optimum conditions, with properties meeting international ASTM D 6751 and EN 14214 standards (Bokhari et al., 2015). This efficient production process contributes to minimizing waste generation and energy consumption, aligning with green chemistry and engineering principles (Martinez-Guerra & Gude, 2017). Interestingly, while Ceiba pentandra offers environmental advantages, it's important to note that microalgae-based biodiesel production may provide even greater benefits due to its numerous advantages over terrestrial plants (Gong & Jiang, 2011). Additionally, the environmental impact of biodiesel production from cottonseed has been studied, highlighting the need to address hotspots in the production chain to improve sustainability (Motevali et al., 2023). In conclusion, Ceiba pentandra-based biodiesel presents a promising alternative to fossil fuels, offering benefits such as renewability, biodegradability, and reduced toxicity (Živković & Veljković, 2017). However, to maximize its environmental potential, ongoing research and optimization of production processes are necessary to minimize costs and environmental impacts throughout the entire lifecycle (Jamaluddin et al., 2019; Ramos et al., 2019).

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CHALLENGES OF USING BIODIESEL FROM WCO IN AVIATION

One of the primary challenges is the economic viability of Ceiba pentandra-based biodiesel production. A techno-economic analysis of a 50 ktons Ceiba pentandra biodiesel processing plant with a 20-year lifespan revealed an investment of around $701 million with a 3.7-year payback period (Jamaluddin et al., 2019). This significant initial investment and relatively long payback period could be deterrents for potential investors. Additionally, the study highlighted the need for continuous improvement in conversion processes and operational efficiency to decrease production costs (Jamaluddin et al., 2019). Interestingly, while Ceiba pentandra offers promise, the biodiesel industry as a whole faces challenges related to high production costs, large acreage requirements for oil-yielding crops, and competition with food production (Uthandi et al., 2021). These factors have led researchers to explore alternative approaches, such as microbial oils, which offer advantages like shorter life cycles and easier scalability (Uthandi et al., 2021). In conclusion, while Ceiba pentandra presents an opportunity for biodiesel production, particularly in Southeast Asia, challenges remain in terms of economic viability and process optimization. Further research is needed to fully utilize Ceiba pentandra as a non-edible source of biodiesel (Jamaluddin et al., 2019), potentially focusing on improving conversion processes, increasing operational efficiency, and addressing the broader challenges faced by the biodiesel industry.

4. COST ANALYSIS OF BIODIESEL PRODUCTION FROM WCO

One of the primary challenges is the economic viability of Ceiba pentandra-based biodiesel production. A techno-economic analysis of a 50 ktons Ceiba pentandra biodiesel processing plant with a 20-year lifespan revealed an investment of around $701 million with a 3.7-year payback period (Jamaluddin et al., 2019). This significant initial investment and relatively long payback period could be deterrents for potential investors. Additionally, the study highlighted the need for continuous improvement in conversion processes and operational efficiency to decrease production costs (Jamaluddin et al., 2019). Interestingly, while Ceiba pentandra offers promise, the biodiesel industry as a whole faces challenges related to high production costs, large acreage requirements for oil-yielding crops, and competition with food production (Uthandi et al., 2021). These factors have led researchers to explore alternative approaches, such as microbial oils, which offer advantages like shorter life cycles and easier scalability (Uthandi et al., 2021). In conclusion, while Ceiba pentandra presents an opportunity for biodiesel production, particularly in Southeast Asia, challenges remain in terms of economic viability and process optimization. Further research is needed to fully utilize Ceiba pentandra as a non-edible source of biodiesel (Jamaluddin et al., 2019), potentially focusing on improving conversion processes, increasing operational efficiency, and addressing the broader challenges faced by the biodiesel industry.

5. CONCLUSION

This review underscores the viability and promise of Ceiba pentandra (silk cotton seed oil) as a non-edible, sustainable feedstock for biodiesel production. With an oil yield of 20–25% and a favorable fatty acid profile—rich in palmitic, oleic, linoleic, and stearic acids—Ceiba pentandra offers an environmentally responsible alternative to edible oils. Its ability to grow on marginal lands with minimal input makes it particularly suitable for resource-constrained regions. Importantly, biodiesel derived from this oil meets ASTM D6751 and EN 14214 standards, validating its compatibility with existing diesel infrastructure. The application of heterogeneous acid catalysts, particularly zeolite-diatom composites, has been shown to enhance conversion efficiency, simplify post-reaction purification, and reduce waste. These catalysts demonstrate reusability, high thermal stability, and the ability to process high-FFA feedstocks efficiently, positioning them as next-generation solutions for scalable production. However, challenges persist, particularly regarding the high initial investment—estimated at $701 million for a 50-kiloton plant—and the need for continued process optimization to ensure economic feasibility. While Ceiba pentandra-based biodiesel shows great potential for reducing fossil fuel reliance and promoting sustainable energy, further research into improving catalyst longevity, production efficiency, and lifecycle cost reduction is essential for its commercial success and broader adoption in sectors like transportation and aviation.

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