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SUSTAINABLE AVIATION: BIODIESEL FROM WASTE COOKING OIL AS A PROMISING ALTERNATIVE FUEL BLEND

Nithin G[*1], Harish Raj C[*2], Alagar K[*3], Dawn SS[*4]

[*1]Department Of Chemical Engineering, Sathybama Institute Of Science And Technology, Chennai, Tamilnadu, India.

[*2]Centre For Waste Management. Sathybama Institute Of Science And Technology, Chennai, Tamilnadu, India.

[*3,4]Centre Of Excellence For Energy Research, Sathybama Institute Of Science And Technology, Chennai, Tamilnadu, India.

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ABSTRACT

With the aviation industry looking to cut its carbon emissions and transition towards cleaner, sustainable fuel sources, waste cooking oil (WCO) biodiesel is one solution that seems to fit. The alternative fuel has a two-fold advantage of recycling waste oil and reducing greenhouse gas emissions substantially even when mixed with regular jet fuel. WCO as a feedstock for biodiesel promotes the circular economy, minimizes waste, and boosts energy security through fuel diversification. In addition, biodiesel blends can be utilized in existing aviation infrastructure to enable a seamless shift to cleaner aviation fuels. While promising, scalability, production, and optimization of blending ratios are among the challenges that need to be overcome for large-scale implementation. This article explores the sustainability of WCO-based biodiesel as an aviation fuel, both its environmental benefits and the challenges to its mass application. The prospect of biodiesel from waste cooking oil in the aviation sector is dependent on advances in technology, policy incentives, and a coordinated effort to surmount existing challenges, making it a central enabler of the long-term sustainability of the aviation sector.

Keywords: Sustainable Aviation Fuel, Waste Cooking Oil, Transesterification, Blends, Biodiesel.

1. INTRODUCTION

Biodiesel is a biodegradable, renewable diesel engine alternative fuel derived from vegetable oils, animal fats, or other biomass with high triacylglycerol content via a transesterification process [1]. It is specifically characterized as mono-alkyl esters of long chain fatty acids and should conform to ASTM D6751 standards [2]. The characteristics of biodiesel are strongly associated with its chemical structure, specifically its fatty acid profile, which is the same as that of the parent fat or oil [1], [3]. Some of the most important characteristics are kinematic viscosity (3.6-4.6 mm^2/s at 311 K), density, cetane number, cloud and pour points, distillation properties, flash and combustion points, and higher heating value [2]. Biodiesel also has a number of benefits when compared to petrodiesel such as biodegradability, increased flash point, lower exhaust emissions, solubility with petrodiesel, compatibility with the current infrastructure of fuel and inherent lubricity [1]. Biodiesel also has a number of technical issues like oxidative stability, cold flow characteristics, and higher NOx emissions [1], [4]. These are determined by such factors as fatty acid profile, acid value, peroxide value, iodine value, viscosity, impurities, and storage conditions [4]. The optimization of biodiesel properties has been an area of research by various means, such as using additives and fatty acid profile engineering to produce specific fuel properties[3], [4]. Knowledge of the structure-property relationships of fatty acid esters is important in choosing the right vegetable oils and alcohols to create biodiesel with the best performance [3]

Biodiesel has several environmental benefits compared to conventional fossil fuels. It is a renewable fuel source that can help reduce greenhouse gas emissions and other pollutants.[5] indicates that biodiesel is the first and only alternative fuel to undergo a thorough analysis of emission effects. Biodiesel combustion tends to emit less carbon dioxide and carbon monoxide compared to fossil fuels. Moreover, sulfur emissions are virtually removed with pure biodiesel, and the smog-forming ability of biodiesel hydrocarbons is less compared to diesel fuel [5]. Surprisingly, even though biodiesel proves explicit benefits in limiting some emissions, some inconsistency can be found in its overall effect on the environment. [6] states that biodiesel lowers greenhouse gas emissions by 41% relative to fossil fuels displaced. Though [7] opine that plain combustion emissions of biodiesel can prove to be worse than petroleum diesel fuel combustion emissions in health hazard terms. The complexity of considering the entire environment impact of the use of biodiesel is hence brought out in this context. In summary, biodiesel encompasses a great range of environmental advantage, especially decreasing greenhouse gas emission and air quality pollutants. [6] illustrates how biodiesel generates 93% more energy input into its making and emits lower agricultural pollutants for every net increase in energy as opposed to ethanol. Nevertheless, the possible adverse health effects, and the demands for sustainable production of feedstock [8], are taken into perspective in a true analysis of environmental gains from using biodiesel. Future studies should aim at optimizing production and dealing with possible adverse effects to maximize the environmental benefits of biodiesel consumption.

1.1 WASTE COOKING OIL (WCO)

Waste cooking oil (WCO) is a future-oriented feedstock for biodiesel, being a far better option compared to traditional vegetable oils. It is a renewable, biodegradable, and non-toxic substitute for petrol-based diesel, providing a solution to energy security and environmental concerns [9]. The application of WCO as a feedstock for biodiesel resolves waste management issues and minimizes the conflict between food and fuel resources [10], [11]. Surprisingly, although WCO offers a promising alternative for biodiesel production, it has some challenges. The presence of high free fatty acid (FFA) in WCO is a major limitation, necessitating additional processing steps or secondary catalytic processes [9]. Recent technological advances, like oscillatory flow reactors, ultrasonication, microwave reactors, and co-solvent systems, promise to overcome these challenges[9]. Moreover, the application of heterogeneous catalysts, such as the Ni/Zeolite catalyst prepared from geothermal solid waste, has been promising in WCO processing, with biodiesel yields of up to 89.4 [12]. In summary, biodiesel production from WCO provides a green solution to energy and waste management issues. Its economic feasibility is evident through the estimated cost of production of approximately 0.66 USD [11]. In order to unlock its full potential, governments ought to adopt policies of support such as economic inducements and obligatory regulations, which would encourage restaurants and other WCO producers to channel their waste oil into formal collectors to be used for the production of biodiesel [13]. With the correct research emphasis and development, WCO can become a perfect feedstock for biodiesel, towards a greener energy future.

1.2 ADVANTAGES OF USING WCO FOR BIODIESEL PRODUCTION

Waste cooking oil (WCO) has several merits in terms of biodiesel manufacturing. WCO is an available and cheap raw material for making biodiesel and saves up to 45% on raw materials as compared to virgin oils [14]. WCO also disposes of wastage, rendering it ecofriendly[15]. The recycling of WCO offers a renewable energy source with economic, environmental, and waste management advantages[16]. Surprisingly, even though WCO-derived biodiesel is collected from different sources, it can be produced with high yield and quality. For example, under optimized conditions, a conversion rate of 96% was obtained using calcium oxide (CaO) nano-catalyst [16]. In the same way, a new diatomite CaO/MgO catalyst showed a 96.47% maximum biodiesel yield [17]. Overall, WCO biodiesel production is an environmentally friendly, cost-saving fuel substitute for fossil fuels. It provides lower emissions of CO, HC, PM, and smoke [15], while achieving international biodiesel standards [17]. Nonetheless, issues like shortage of processing technology and irregularity in supply amount must be tackled for mass production [18]. Generally, WCO-based biodiesel offers a bright prospect for the production of renewable energy and waste disposal.

1.3 COLLECTION AND PROCESSING OF WASTE COOKING OIL

Waste cooking oil (WCO) collection and preprocessing are essential processes for using this resource for a range of applications, such as biofuel production and 3D printing materials. There have been various studies on various methods of collection and their efficiency. In urban communities, restaurants are important generators of WCO. A study in Beijing reported that restaurants produced 90.14 thousand tonnes of WCO in 2016, out of which 24% failed to report to formal collectors [13]. In order to enhance collection rates, economic incentives and compulsory regulations were recognized as preponderant forces shaping restaurants' disposal choices. A 4 yuan RMB/kg subsidy was discovered to make all restaurants willing to provide WCO to official collectors [13]. Curiously, the methods of collection can play an important role in determining the economic feasibility of the use of WCO. It has been found by a cost-benefit analysis that collection of WCO with used lubricating oil (System II) was superior to individual collection with chemical treatment (System III)[19]. Nevertheless, program effectiveness can also be determined by local conditions. In Angri, Italy, a shift in management and regional waste management problems resulted in a dramatic reduction in WCO collection, emphasizing the need for regular and well-organized collection systems[20]. In summary, effective WCO collection and preprocessing involve a mix of efficient collection systems, economic incentives, and public awareness. Adoption of these measures can greatly enhance WCO recovery rates and enable its use in different applications, ranging from biofuel production to new applications such as 3D printing materials (Wu et al., 2019).

2. BIODIESEL PRODUCTION

Waste cooking oil (WCO) biodiesel can be produced using different processes, the most preferred one being transesterification. Two-step transesterification is ranked as the most effective process for the production of biodiesel from WCO, particularly for high-free fatty acid feedstocks [15]. The process is initiated with acid-catalyzed esterification followed by base-catalyzed transesterification. A number of innovative methods have been investigated for increasing the efficiency of biodiesel production. Microwave-assisted transesterification has been promising, using less than 10% of the energy used in conventional heating compared to similar yields [21]. Other emerging processes involve membrane reactors, reactive distillation columns, reactive absorption, and ultrasonic irradiation, which have the potential to affect the end conversion, yield, and quality of the final product [22]. The catalyst selection is important in the production of biodiesel. Heterogeneous catalysts like CaO nanoparticles have shown excellent conversion of 96% under optimized conditions [16]. Composite catalysts such as MgO/CaO obtained from industrial waste provide a more green solution for transesterification [23]. Nonetheless, the concentration and catalyst type are some of the most significant factors that impact biodiesel yield[15].To optimize the production process and minimize waste generation, artificial neural network models have been developed to predict biodiesel yield and engine properties [24]. The models possess high regression coefficients and low error rates, and they are effective tools for process optimization.

2.1 CHARACTERISTICS AND PROPERTIES OF BIODIESEL

Biodiesel from waste cooking oil (WCO) has unique features and properties, making it a promising substitute fuel. The transesterification reaction with WCO can produce quality biodiesel with a maximum conversion of 94-96% under favorable conditions [16], [25]. The biodiesel performs similar energy utilization factors to ordinary diesel fuel upon combustion in diesel engines [26]. Yet, biodiesel derived from WCO poses some limitations. It normally consists of poor cold flow properties, low oxidation stability, and lower flash point than conventional [25], [27]. The aforementioned are mostly due to the higher saturated fatty acid content of WCO [28]. Surprisingly, combining WCO with other non-polymeric edible oils, for instance, Schleichera oleosa, is possible to enhance cold flow and oxidation stability without using synthetic additives[25].Furthermore, utilization of bio-based diluents like ethyl acetoacetate has proven to improve cold flow properties and oxidation stability [27]. In summary, although biodiesel from WCO provides a more environmentally friendly and cheaper substitute for traditional diesel, its characteristics have to be taken into account.Bleaching with other oils, addition of bio-based additives, and production refining processes are among the methods that can significantly improve its quality. Carefully produced and blended, WCO biodiesel has the potential to be of international quality and perform satisfactorily in diesel engines with fewer polycyclic aromatic hydrocarbons, particulates, and other pollutants emissions compared to ultra-low sulfur diesel [29].

2.2 EMERGING TECHNOLOGIES FOR BIODIESEL PRODUCTION

New technologies for the production of biodiesel are attracting considerable interest because of their ability to bypass the constraints of traditional processes. These new methods are designed to increase efficiency, lower costs, and make overall biodiesel production more sustainable. Some of the most promising new technologies have been highlighted in recent research. Plasma-assisted transesterification has exhibited great promise with a 99.5% yield in transesterifying soybean oil to biodiesel within seconds [30]. Microwave-assisted, ultrasonic-assisted, and supercritical fluid methods are some other promising technologies with the ability to enhance mass and heat transfer, resulting in faster reaction rates and increased yields [30], [31]. In addition, enzyme-catalyzed transesterification, whole-cell biocatalysts, and magnetic-assisted transesterifications are considered alternatives to the traditional catalytic process[32]. Interestingly, despite the many advantages these new technologies provide, each of them comes with special challenges. For example, the processes of some processes, like non-thermal plasma discharge, are yet to be fully understood [30]. In addition, scale-up of the technologies at industrial levels is an area of extreme importance for research in the future [32]. Albeit with the above challenges, the advantages posed by emerging technologies, such as lower production cost, enhanced efficiency, and diminished environmental footprint, render them eligible candidates for potential future biodiesel[31], [32], [33].

3. AVIATION FUEL REQUIREMENTS AND SPECIFICATIONS

Aviation turbine engine fuel standards are mostly regulated by ASTM International and the British Ministry of Defence (MOD). ASTM D1655 and MOD Defence Standard 91-91 are the standard specifications for aviation fuel globally [34]. These standards are derived from extensive experience with traditional fuel sources and provide acceptable characteristics for turbine engine application. For sustainable aviation fuels (SAFs), ASTM D7566 and Annex D of DS91-91 also include requirements for synthetic [34], [35]. Surprisingly, although SAFs are perceived to be key for lowering carbon emissions, they are presently restricted to a maximum 50% blend with regular jet fuel [36].The limitation is also due in part to o-ring swelling, which must remain consistent. Nevertheless, research finds that it becomes possible to maintain swelling in the conventional fuel range with less than 8% aromatics despite current specifications [36]. Other research also indicates that pristine biofuels from microalgae may not meet all the jet fuel requirements, particularly density, heating value, and freezing point [37].Put simply, aviation fuel requirements are being altered to include new sustainable fuels without ever sacrificing safety and performance. SAF standards development is designed to achieve more safety with fewer constraints[35]. With the aviation industry targeting net-zero emissions by 2050, ongoing research and potential revisions to current specifications may be necessary to enable new biofuels to be added while they can meet the stringent requirements of aviation fuels [37], [38].

3.1 BLENDING BIODIESEL WITH CONVENTIONAL AVIATION FUEL

Biodiesel blends with fossil aviation fuel have been found to be encouraging from the point of view of engine performance and emission reduction. Tests have proven that biodiesel is suitable for application in gas turbine engines at up to a 50% blend with Jet A-1 fuel, with a slight improvement in engine performance and considerable reduction in exhaust emissions [39]. For example, the static thrust of the engine was 2% higher for B50 (50% biodiesel blend) at low and medium engine speeds, and the thrust-specific fuel consumption was less than that of conventional Jet A-1 fuel[39]. Surprisingly, various studies have shown different optimal blending ratios. Though Ali and Ibrahim (2016) recommends up to 50% biodiesel blend, Altarazi et al. (2021)[40] identified that the B10-Jet blend (10% biodiesel) produced the optimum specific fuel consumption value and reduced emissions of CO and CO2 when compared to Jet-A fuel and other blends.Ali et al. (2015)[41] demonstrates that characteristics of blended fuels meet standard specifications at the maximum of 30% palm oil biodiesel. The disparities highlight the necessity of considering specific biodiesel sources and types of engines in determining the best blending ratios. But at airport level, biodiesel blends with conventional aviation fuel is pose a considerable increase margin for minimising environmental footprint and its performance on engine operation is acceptable.The application of biodiesel blends can result in lower emissions of CO, HC, and SO2, though minor increases in CO2 and NOx emissions have been noted [39]. Yet, the ideal blending proportion will differ in relation to the biodiesel origin and engine configuration, calling for more studies on identifying the best and most economical blending methods applicable for various purposes in the air transport sector.

3.2 ENVIRONMENTAL IMPACT OF BIODIESEL-AVIATION FUEL BLENDS

Biodiesel-aviation fuel blends have exhibited promising environmental advantages over traditional petroleum-based fuels. Research has shown that the blends are capable of lowering particulate matter (PM), total hydrocarbon (THC), and carbon monoxide (CO) emissions in both aircraft and diesel engines [42], [43]. The decrease in emissions tends to be in proportion to the percentage increase in biodiesel in the blend. Notably, the effect on nitrogen oxide (NOx) emissions differs based on biodiesel type and blend ratio. Some researchers documented higher NOx emissions at increased biodiesel concentrations[42], whereas others showed no appreciable difference or even minor reductions in NOx emissions[40], [44]. This difference is a sign of the complexity of emission patterns and requires further studies. Lastly, biodiesel-aviation fuel blends have potential environmental benefits, particularly for reducing PM, THC, and CO emissions. However, their impact on NOx emissions varies between studies. Applying these blends can have the potential to reduce local air pollution and minimize greenhouse gas emissions for aviation[43], [45]. Additional research would be needed to fine-tune blend formulations and engine settings in order to provide the maximum environmental benefit while maintaining performance requirements.

3.3 CHALLENGES OF USING BIODIESEL FROM WCO IN AVIATION

Waste cooking oil (WCO) biodiesel encounters a number of challenges for its application in the aviation sector: The high content of saturated fatty acids in biodiesel from WCO can create poor cold flow properties, an important issue in aviation fuels which must operate efficiently at low temperatures at high altitudes[27]. This problem can actually be solved using additives such as ethyl acetoacetate, which enhanced cold filter plugging point and pour point upon mixing with WCO biodiesel [27]. Although WCO biodiesel has environmental advantages such as less emission of polycyclic aromatic hydrocarbons and other harmful substances over normal diesel[29], aviation fuel applications have higher fuel quality specifications. It may be difficult to meet these specifications regularly with WCO feedstock because of variability in waste oil composition and contaminants. Severe pretreatment and purification processes are usually required [46]. From the economic standpoint, although WCO is a cheaper feedstock, the overall cost of producing the aviation-grade biofuel might also be expensive with the necessity to use catalysts, machinery, and multi-staged conversion[47], [48].Optimizing reaction conditions and exploring process intensification techniques like microwave heating could potentially improve yields and reduce costs[46], [47], [48].In conclusion, while WCO biodiesel shows promise for reducing environmental impact and utilizing waste resources, significant technical and economic hurdles remain for its widespread adoption in aviation. More research into refining fuel properties, maximizing production procedures, and providing quality consistency will be essential in addressing these challenges.

4. COST ANALYSIS OF BIODIESEL PRODUCTION FROM WCO

The production of biodiesel from waste cooking oil (WCO) has considerable economic benefits over conventional feedstocks. The production cost of biodiesel from WCO is in the range of Rs. 51-55/kg[49] to US$ 0.17-0.52/L based on plant capacity[50]. The total energy input and output for the production of biodiesel are 30.05 and 44.91 MJ L^{-1} respectively, with an energy output/input ratio of 1.49 [51]. Benefit-to-cost ratio is approximately 2.081, with net return

1.298 $ L−1 [51]. Interestingly, although WCO is a low-priced commodity in commerce, pretreatment procedure takes up 15.60% of the production cost [52]. It indicates the significance of upgrading waste cooking oil recycling technology for higher economic competitiveness. Furthermore, the supercritical transesterification process has benefits by removing pre-treatment expenses of water and free fatty acids in WCO [50]. In summary, biodiesel production from WCO is economically feasible, with production expenses 65.28% more than diesel [52]. The major factors affecting economic viability are raw material price, plant capacity, glycerol price, and capital cost [50]. In order to make it more competitive, special policies for waste management and enhanced recycling technology of WCO are key [52]. In summary, WCO biodiesel manufacturing is a bright prospect for reuse of waste resources and renewable energy generation, withstanding existing market difficulties [53].

5. CONCLUSION

Furthermore, WCO biodiesel has shown 96% conversion efficiency under optimum conditions with the help of catalysts like calcium oxide (CaO) nano-catalysts. Notwithstanding its benefits, challenges are associated with it such as low cold flow properties by virtue of having high saturated fatty acid content, fluctuation in feedstock quality, and requiring severe refining for meeting aviation fuels like ASTM D7566. The cost of WCO biodiesel production varies between ₹51-55/kg ($0.17-0.52/L), with energy output/input ratios of 1.49, and is a competitive renewable fuel. Microwave-assisted Waste cooking oil (WCO)-based biodiesel is also a promising candidate for sustainable aviation fuel (SAF) with huge economic and environmental advantages. Studies have estimated that WCO biodiesel can cut down the greenhouse gas emissions by a potential 41% when compared to fossil fuels, as well as decrease particulate matter (PM), total hydrocarbon (THC), and carbon monoxide (CO) emissions. In other words, WCO biodiesel has demonstrated up to 96% conversion efficiency under ideal conditions with catalysts such as calcium oxide (CaO) nano-catalysts. Despite its advantages, WCO biodiesel is hampered by poor cold flow properties due to high content of saturated fatty acids, variations in feedstock composition, and the need for high-refining to aviation levels such as ASTM D7566. WCO biodiesel can be manufactured for ₹51-55/kg (about $0.17-0.52/L) energy output/input of 1.49, a cost that renders it competitive as a renewable fuel. Emerging technologies like microwave-assisted transesterification, plasma-assisted processing, and heterogeneous catalysis present promising channels to improve the quality of fuels and lower their cost of manufacture. In addition, policy incentives, effective WCO collection systems, and blending techniques (e.g., optimal biodiesel-aviation fuel blending ratios, B10-Jet blending) are essential to ensure large-scale uptake. Further research, policy support, and process optimization can make WCO-based biodiesel a vital driver for aviation decarbonization and the achievement of the 2050 net-zero emissions target. transesterification, plasma-assisted processing, and heterogeneous catalysis are some of the new technologies that have some potential solutions to enhance fuel quality and reduce the cost of manufacturing.

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