

Research Paper

Plasma Enhanced Ionic Liquid Catalysis for the Production of Biodiesel from Chicken Skin

Yasir Ali Elsheikh[✉], Hamed Al Mahri, Asma Al Mamari, Khisbullah Hudha

Department of Chemical and Petrochemical Engineering, Faculty of Engineering and Architecture, University of Nizwa, P.O. Box 33, Postal Code 616, Sultanate of Oman

[✉] yasir.elfadol@unizwa.edu.om

<https://doi.org/10.31603/ae.13397>

Published by Automotive Laboratory of Universitas Muhammadiyah Magelang

Article Info

Submitted:

13/04/2025

Revised:

13/07/2025

Accepted:

19/08/2025

Online first:

28/08/2025

Abstract

Biodiesel production has emerged as a promising area of alternative fuel development, though challenges remain in sourcing cost-effective raw materials and selecting effective catalysts. This study investigates the production of biodiesel from chicken skin fat using two distinct catalytic methods. In the first method, transesterification was catalyzed by trioctyl ammonium hydrogen sulfate ($\text{Oct}_3\text{AMHSO}_4$) at concentrations ranging from 3-6 wt%. In the second method, the same catalyst was combined with plasma to enhance the reaction. The first method yielded only 35% biodiesel with 3.5 wt% $\text{Oct}_3\text{AMHSO}_4$, while the second method, under identical conditions, showed a significant improvement, achieving a 97.4% yield. The impact of temperature variations (40-80 °C) was also explored with different catalyst concentrations (3-6 wt%). Increasing the catalyst concentration to 3.5% and raising the temperature to 55 °C resulted in a notable yield improvement. However, further increases in temperature or catalyst concentration beyond 3.5% led to a decline in yield, particularly at temperatures exceeding 60 °C. This suggests that certain reaction conditions may reverse the transesterification process, pushing the products back toward the reactants and reducing efficiency. For $\text{Oct}_3\text{AMHSO}_4$ -plasma catalyzed- transesterification, a maximum yield of 97.4% was achieved under optimal conditions of a 6:1 molar ratio, $\text{Oct}_3\text{AMHSO}_4$ of 3.5 wt%, and 60 °C for 60 min operating time. For five recycling experiments, the yield data appears constant. This means that the catalyst can withstand many recycling processes, which could have a positive economic impact on this process.

Keywords: Biodiesel production; Ionic liquid catalysis; Plasma-enhanced catalysis; Transesterification; Chicken skin fat

1. Introduction

The global poultry industry produces significant quantities of chicken skin and fat, which are often discarded as waste. Chicken skin and visible fat typically make up around 8-20% of the total weight of a chicken carcass, yet this by-product is frequently undervalued [1]. In countries like Malaysia, where annual poultry production reaches approximately 74,016 tons, a substantial amount of chicken fat remains underutilized. Similarly, Brazil, one of the world's largest poultry producers, generates around 440,000 tons of poultry by-products, including

skin and fat, annually [2]. This widespread waste of chicken fat contributes to environmental challenges such as landfill overflow and pollution [3]. In Oman, the expanding poultry industry has only intensified this problem, with rising production volumes leading to increased disposal of chicken skin fat, further exacerbating environmental and waste management issues [4].

Fossil fuels, including diesel, gasoline, oil, natural gas, and even coal, are the main cause of climate change and the majority of air pollution. Globally, as of 2011, fossil fuels represented around 80% of the total primary energy supply used for electricity production, industry, and



This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License.

transportation [5]. The increasing demand for energy and pollution problems resulting from the use of fossil fuels has caused the global economy to urge the international and scientific community to focus more on finding urgent and sustainable alternatives to meet the global market's energy needs and environmental protection requirements [6]. Some available and environmentally acceptable sources are vegetable oils [7], animal fats [8], and their wastes [9]. More than ever, the idea of converting waste into valuable products is considered a strategic goal that keeps pace with ongoing global exploration and trends to reduce environmental pollution and waste of raw food materials that are important to humans, such as edible oils [10], [11]. Recent studies have produced biodiesel from chicken waste using strong alkaline catalysts commonly used for esterification reactions, such as potassium and sodium hydroxides. The yield did not exceed 48% under the optimum reaction conditions [12], [13].

This research investigates the potential of using chicken skin fat, a commonly discarded by-product of the poultry industry, for biodiesel production through two catalytic approaches. The first method employs transesterification with trioctyl ammonium hydrogen sulfate ($\text{Oct}_3\text{AMHSO}_4$) at different concentrations, while the second method incorporates plasma to enhance the catalytic process. The study aims to optimize the reaction conditions by evaluating the effects of temperature (ranging from 40 to 80 °C) and catalyst concentration (from 3 to 6 wt%) on the biodiesel yield. The primary goal is to maximize the conversion of chicken skin fat into biodiesel, addressing both the waste management challenge and the growing need for alternative, eco-friendly energy sources. This approach offers the potential to reduce environmental impact and provide a viable renewable energy solution.

Biodiesel is primarily composed of alkyl monoesters derived from fatty acids in vegetable oils, animal fats, or their by-products. Currently, biodiesel production mostly relies on transesterifying soybean oil with alcohol in the presence of an alkaline catalyst [14]. However, the high production cost of biodiesel, often more than double that of petrol, is largely due to the expensive extraction and processing of vegetable oils. To address this, many researchers suggest using waste oils and fats, as raw material costs

play a significant role in biodiesel pricing. The increasing volume of waste animal fats, particularly from chicken, cows, and sheep, raises environmental concerns, making it essential to explore their potential use in biodiesel production [15], [16]. A key challenge is that waste oils and animal fats often contain high levels of free fatty acids (FFAs), which react with alkaline catalysts, forming soap that inhibits the separation of ester from glycerin and other reactants [17].

In recent years, ionic liquids (ILs) have gained significant attention as an alternative to traditional solvents and catalysts. Their unique properties—such as customizable melting points, viscosities, and solubility—make ILs highly versatile and effective in various chemical processes. For biodiesel production, ILs have shown the potential to overcome many of the limitations associated with conventional alkaline catalysts, including better separation of products and a reduction in waste generation [18]. Moreover, ILs can be tailored to optimize reaction conditions, making them a promising candidate for biodiesel production from waste oils and fats. Studies have demonstrated the ability of ILs to catalyze transesterification reactions efficiently, often achieving high biodiesel yields. For example, Wu *et al.* [19] achieved a 92% yield using ILs with imidazolium and pyridinium cations for cottonseed oil transesterification, while another study achieved 94.5% yield with a pyridine-based IL for soybean oil [20].

Despite their advantages, the use of ILs in biodiesel production is not without challenges. One significant issue is the high boiling point of methanol, which is commonly used in transesterification reactions. The boiling point of methanol does not exceed 65 °C, and excessive heat can lead to the formation of superheated vapor, complicating the separation process. Additionally, the use of large quantities of methanol can cause emulsification, making it difficult to separate the biodiesel from the glycerin and other by-products. These challenges contribute to increased production costs and reduced overall efficiency. As such, there is a growing need to explore alternative methods or modifications to enhance the efficiency of ILs and reduce the negative impact of methanol on the production process.

Nonthermal plasma (NTP), also known as cold plasma, has emerged as a promising technology to improve chemical catalysis, including biodiesel production. NTP generates highly reactive species such as ions, electrons, and radicals, which can facilitate chemical reactions without generating harmful by-products. Recent research has demonstrated that NTP can enhance catalytic reactions, providing an environmentally friendly and efficient alternative to traditional heating methods. NTP has already shown its potential in various chemical processes, including biodiesel production, by improving the overall yield and reducing reaction times. As a green catalytic material, NTP aligns with the broader goal of sustainable energy production and environmental protection [21].

The present research aims to explore the combined use of ionic liquids and nonthermal plasma to enhance biodiesel production from chicken skin fat. In the first approach, Oct₃AMHSO₄ is used as the primary catalyst, while in the second, plasma exposure is applied to optimize the reaction process. Both methods will be evaluated under similar reaction conditions, including catalyst concentration, temperature, and methanol-to-fat ratio. The study also focuses on understanding the effects of varying temperatures and catalyst concentrations on biodiesel yield, with a consistent molar ratio of 6:1 (methanol to fat) and a stirring rate of 600 rpm. By investigating the synergies between ILs and NTP, this research aims to identify an efficient and sustainable process for biodiesel production that can be scaled up for industrial applications.

2. Materials and Methods

2.1. Materials

The materials used in this study were of analytical grade and sourced from reputable suppliers. All chemicals were employed as received, without any additional drying or purification steps, ensuring their purity was consistent with the supplier specifications. The following chemicals were utilized:

- Triethylamine ($\geq 98.0\%$): Used as received to synthesize the catalyst (Oct₃AMHSO₄), essential for the transesterification reaction.
- Sulfuric Acid ($>97\%$): Applied in concentrated form to catalyze esterification, converting FFAs into biodiesel.

- n-Hexane (99%): A non-polar solvent used to extract biodiesel and separate glycerin, with no further purification.
- Toluene ($>99.8\%$): Served as a solvent and wash agent to remove impurities from the reaction products.
- Acetonitrile ($\geq 99.8\%$): Used in analysis and catalyst preparation due to its stability and low interference.
- Methanol (99.8%): Reacted with fatty acids in the transesterification process to form biodiesel.
- Diethyl Ether ($\geq 99.8\%$): Used to extract biodiesel from by-products, chosen for its effective solubility and purity.

All reagents were used directly from their commercial sources without any drying procedures or further purification, as they met the necessary standards for the required reactions. The chemicals were stored according to the suppliers' guidelines to maintain their stability and prevent degradation prior to use.

2.2. Fats Extraction

Chicken skin was sourced from local restaurants, and fat extraction was carried out using a conventional Soxhlet apparatus. In this process, n-hexane was employed as the solvent in the lower flask to effectively separate the lipid components from the solid matrix. Following extraction, the solvent was removed from the fat extract using a rotary evaporator to obtain purified chicken fat.

2.3. Characterization of Chicken skin

The fatty acid composition of the extracted chicken skin fat was determined using a Shimadzu gas chromatography (GC) system, in accordance with the standardized procedure outlined in AOCS Official Method Ce 1-62. Prior to analysis, the fat samples were converted to their corresponding fatty acid methyl esters (FAMES) to enhance volatility and accuracy in detection. The chromatographic analysis revealed that oleic acid (C18:1), palmitic acid (C16:0), and linoleic acid (C18:2) were the dominant fatty acids in the sample, making up the majority of the lipid profile. Additionally, minor fatty acids such as palmitoleic (C16:1), stearic (C18:0), linolenic (C18:3), myristic (C14:0), and gadoleic acid (C20:1) were detected in smaller proportions. These

findings reflect the typical composition of poultry fat, with a balance of saturated and unsaturated fatty acids relevant to biodiesel production.

2.4. Preparation of Ionic Liquid

Ionic liquids (ILs) are highly sensitive to both moisture and air, which can alter their properties and catalytic activity. To mitigate this, nitrogen (N_2) gas was introduced into the reactor prior to adding the reactants. The nitrogen was directed through the reactor and condenser, then passed into a gas bubbler, ensuring an inert atmosphere throughout the process [22]. This step was crucial to prevent moisture from contaminating the ILs. Additionally, sulfuric acid, used in the metathesis reaction, is hygroscopic and can rapidly absorb water vapor from the air, leading to dilution of its concentration. Such dilution would diminish the acid's catalytic efficiency and negatively impact the synthesis of the ILs [23].

As illustrated in [Figure 1](#), Oct_3AMHSO_4 was prepared as follows: a 250 mL three-necked, round-bottom flask equipped with a condenser in a magnetic stirrer was charged with octylamine cation route (0.6 mol, 77.5 g) dissolved in 50 mL anhydrous acetonitrile. Then, 32 mL of H_2SO_4 was dropped gradually into the amine solution at ice-cold conditions. Subsequently, the mixture was stirred for 3 hours at room temperature. The obtained product was washed repeatedly with diethyl ether, and finally, under vacuum drying conditions, the produced sample was dried at 60 °C and 25 mmHg for 6 h, giving Oct_3AMHSO_4 . ^1H NMR spectra were recorded at 400 MHz on a Bruker Avance spectrometer with $CDCl_3$ as solvent. The chemical shifts (in ppm) were specified as follows: δ = 0.887 (t, 9H), 1.273 (m, 30H), 1.607 (m, 6H); 3.097 (t, 6H), 6.271 (s, NH), 8.972 (s, H).

2.5. Oct_3AMHSO_4 -Catalyzed Transesterification of Chicken Skin Fats

This section evaluates the performance of Oct_3AMHSO_4 as the primary catalyst for the transesterification reaction. Catalyst amounts ranging from 3 to 6 wt% were tested to enhance the reaction rate. A 40 g sample of extracted fat was reacted in a 250 mL two-neck round-bottom reactor, immersed in silicone oil and equipped with a thermocouple for temperature control, and a magnetic stirrer hot plate with a reflux

condenser. Once the target temperature (40–90 °C) was reached, a methanolic solution was added, prepared by mixing 6 mol of methanol per mol of fat with the catalyst, calculated as a weight percentage of fat. Other reaction parameters, such as reaction time and stirring speed, were set at 60 min and 600 rpm, respectively. After the reaction, the lower layer was removed from the separatory funnel, and the upper layer was washed three times with diethyl ether to remove the catalyst. Despite these conditions, the highest biodiesel yield achieved was 35%.

2.6. IL Recovery and Reuse

In chemical reactions, recovering a homogeneous catalyst typically poses a significant challenge to researchers, as its recovery and reproducibility are key aspects of sustainable chemical processes and economic viability. These challenges are generally due to several factors, including the difficulty of separating the catalyst from the reaction mixture and the risk of deactivation during reactions. These challenges also include the cost and complexity of recovery steps, as well as the potential for catalyst degradation during the recovery process [24].

On completion of the transesterification reaction, a rotovap under vacuum at room temperature is used for the efficient and gentle diethyl ether removal from Oct_3AMHSO_4 to examine its reproducibility and recyclability in this process.

2.7. NTP Treatment

In recent years, non-thermal plasma (NTP) has attracted significant attention due to its numerous advantages. It has been recognized for its ability to effectively alter the surface characteristics of a variety of materials, making it a valuable tool in the development and regeneration of catalytic materials. This capability has opened up new avenues for enhancing catalytic efficiency and performance. Additionally, NTP has proven effective in driving complex chemical reactions under mild conditions, providing an opportunity to conduct transformations that would typically require harsh environments. The versatility of NTP makes it a promising candidate for replacing traditional thermal activation methods, offering a more energy-efficient and potentially sustainable alternative in industrial applications [25].

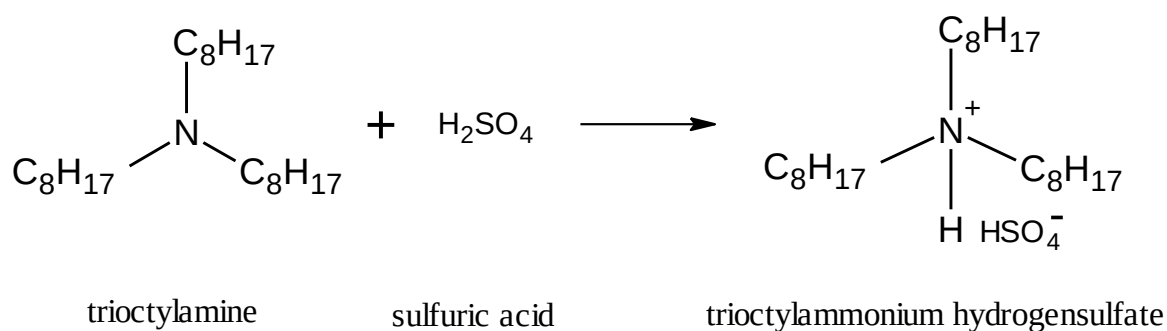


Figure 1. The synthesis procedure of an Oct₃AMHSO₄

2.8. Plasma-Activated Oct₃AMHSO₄-Catalyzed Transesterification

As previously noted, the catalyst showed limited effectiveness under standard thermal conditions. Adjustments in both its concentration and reaction temperature failed to produce any noticeable acceleration in the transesterification process or improvement in biodiesel output. This outcome suggested that, in the absence of additional energy input or activation, the catalyst lacked sufficient reactivity. To further examine its potential, the same reaction system was revisited under plasma-enhanced conditions, with all other variables kept constant. The intention was to determine whether the interaction with plasma-generated energetic species could activate the catalyst surface and trigger the desired chemical transformation more effectively.

Figure 2 shows the schematic setup of a gas-liquid NTP system for the reaction catalysis system, with some subtle modifications to suit our process; this experiment was designed similarly to one of the previous designs that treated seeds contaminated with fungal pathogens. Argon gas employed at higher flow rates of 20 SCCM whereas a common discharge frequency was fixed at of 100 kHz [26]. In general, our system consists of a high-voltage power supply, a controlled flow of argon gas, and a transesterification reactor that includes a plasma electrode tube. The reactor, a round-bottomed flask, contains the reactants (fats and alcohols) in the presence of Oct₃AMHSO₄ at the same concentrations mentioned above (3-6 wt%).

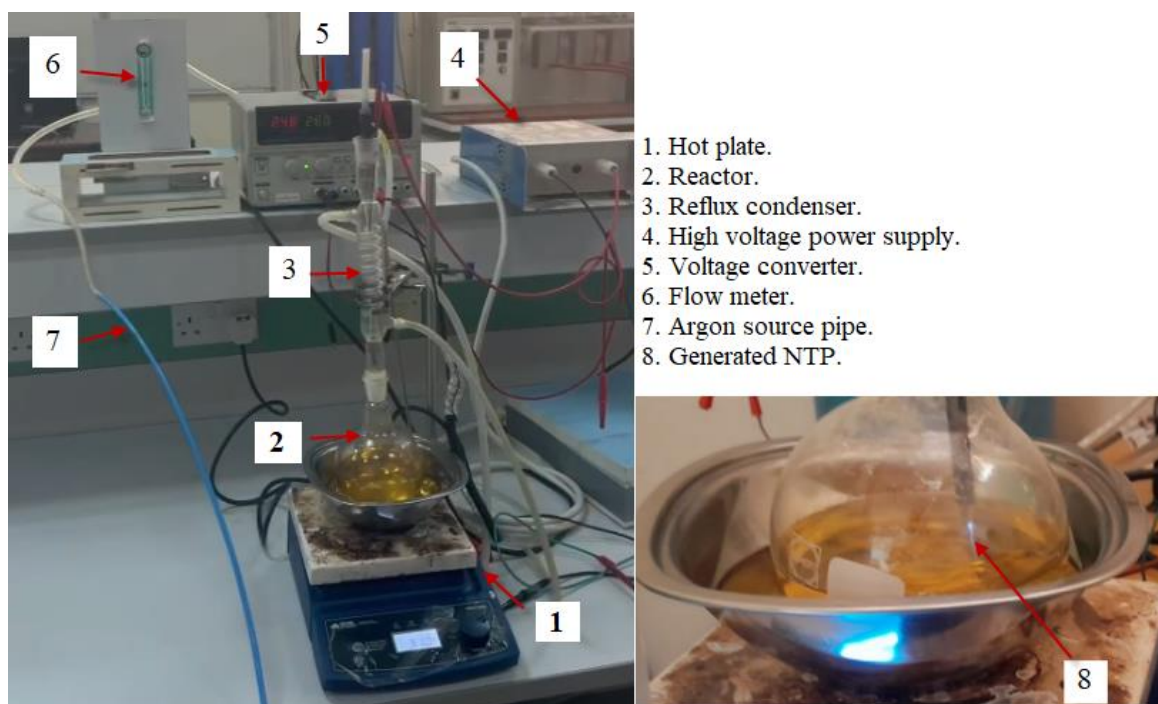


Figure 2. NTP system detailed experimental setup

The prospective plasma was generated in a glass capillary tube. It has an outer diameter of 6.0 mm, a thickness of about 1.0 mm, and a considerable length (50 cm) that can pass through the reflux condenser and reach a close distance to the surface of the reaction medium. The distance between the upper surface of the reaction sample and the plasma electrode bustle is 55–60 cm. The internal cathode is stainless steel 316, and the anode electrode is a thick copper plate. The anode electrode was placed outside the tube in front of the needle, and in order to prevent discharge between the base and the needle, it was covered with a rubber seal as an insulator. After setting the argon gas flow at a rate not to exceed 4.0 L/min, the plasma electrode was electrically connected to a source with a maximum output of 20 kV, an output current of 30 mA, and a voltage of 5 kW. A sample was taken every 10 min at regular intervals to monitor product development during the reaction. After reaching the specified study time (60 min), the argon flow valve was closed, the degassing process was stopped, and the resulting samples were sent for GC analysis.

2.9. Biodiesel Samples Analysis

The collected samples were analysed in triplicate on an SP-2330 capillary Shimadzu GC. The capillary column consists of an automatic sampling system and a flame ionization detector (FID), with a length of 60 m, 0.25 mm ID, and standard film thickness of 0.2 µm. The oven temperature was maintained at 150 °C for 5 min and then raised to 210 °C at 3 °C/min. At a rate of 0.8 mL/min and a split ratio of 100:1, high-purity helium (≥99.95 mol%) was used as a carrier gas and an auxiliary gas for the detector. After dissolving it in n-hexane, 10 µl of each sample was injected into the column injection port, whose temperature was equal to the detector temperature.

3. Results and discussion

3.1. Characterization of the Produced Biodiesel

Table 1 outlines the fatty acid methyl ester (FAME) profile found in biodiesel made from chicken fat. The dominant compounds are methyl oleate (31.4%), methyl palmitate (24.8%), and methyl linoleate (22.1%). These esters are

generated when chicken fat reacts with methanol in a catalytic process [27]. Methyl oleate improves overall fuel performance due to its favorable combustion traits [28]. Saturated esters like palmitate and stearate add to the biodiesel's shelf life but may raise its cold temperature limits [29]. On the other hand, unsaturated esters such as linoleate and linolenate enhance fluidity in cold environments [30]. Minor esters like myristate, gadoleate, and palmitoleate contribute slightly to the mix. Overall, the composition supports efficient use as a renewable fuel with balanced qualities.

3.2. Optimization of Transesterification Reaction

3.2.1. IL concentration effects on catalysis with and without plasma

Figure 3 presents the influence of varying concentrations of the ionic liquid catalyst (Oct₃AMHSO₄) on biodiesel yield, conducted under fixed transesterification parameters: a 6:1 molar ratio, 55 °C reaction temperature, and 60-min duration. The comparison includes reactions performed both with and without the application of plasma. In trials without plasma, the process showed limited efficiency; at 3 wt% IL, the yield did not exceed 25%. Increasing the IL loading to 4 wt% led to a moderate rise in yield to around 35%. However, further elevation to 6 wt% failed to produce additional improvement, suggesting a saturation point in catalytic effectiveness under these conditions. This trend indicates that, in the absence of plasma assistance, simply increasing catalyst concentration does not significantly enhance conversion. The findings highlight the necessity of plasma exposure to activate or accelerate the catalytic process for better biodiesel output.

Table 1. Fatty acid esters contents of chicken fats biodiesel

Species	Fatty acid esters content (% mass)
Methyl myristate	1
Methyl palmitate	24.8
Methyl stearate	4.4
Methyl palmitoleate	4.5
Methyl oleate	31.4
Methyl linoleate	22.1
Methyl linolenate	1.4
Methyl gadoleate	1.1

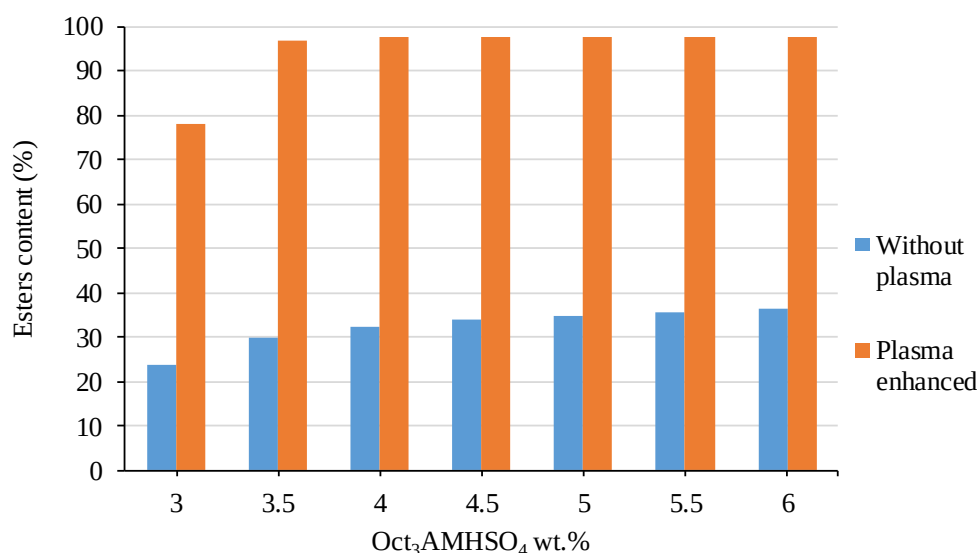


Figure 3. Biodiesel yield % versus IL concentration with and without plasma

The activation of gas molecules by energetic electrons in plasma has shown significant potential in promoting difficult chemical reactions under mild conditions such as room temperature and atmospheric pressure. Despite its high reactivity, plasma tends to lack selectivity, which can limit its effectiveness in targeted processes [31]. To address this limitation, the ionic liquid Oct₃AMHSO₄ was employed as a catalyst to investigate how plasma could influence biodiesel yield under identical transesterification conditions. Figure 3 highlights the noticeable impact of plasma, where using just 3 wt% of the catalyst resulted in over 75% yield—a substantial improvement of more than 55% compared to the same setup without plasma. Further increasing the catalyst concentration to 3.5 wt% boosted the yield to a peak value of 97.3%. However, increasing the concentration to 6 wt% produced no additional improvement, indicating a saturation point had been reached.

These results point to the effectiveness of combining plasma with a relatively small amount of ionic liquid catalyst. Not only does this approach achieve high conversion efficiency, but it also avoids the drawbacks associated with higher catalyst dosages. According to Kroeze *et al.* [32], increasing the amount of catalyst beyond a certain level does not necessarily accelerate the reaction and may even hinder performance due to separation challenges. Excess catalyst can complicate post-reaction recovery, raising concerns about both process efficiency and overall

cost. In practical applications, using more catalyst than necessary may reduce the economic feasibility of biodiesel production. Therefore, the study emphasizes the importance of catalyst optimization to ensure both performance and sustainability in plasma-assisted biodiesel synthesis.

Comparative analysis of the two approaches—catalysis with and without plasma—reveals a clear advantage of the plasma-assisted method. The limited performance of ionic liquid alone may be attributed to its surface properties and the nature of the reaction mechanism. However, the presence of plasma appears to enhance the effectiveness of the catalyst, possibly by modifying its surface structure or composition. Wang *et al.* [33] suggest that plasma catalysis works by generating reactive species and transferring them to the catalyst surface, which can lead to improved reaction kinetics. This synergistic effect likely explains the enhanced activity of Oct₃AMHSO₄ observed in this study. Overall, the results demonstrate that plasma not only activates the reaction medium but also enhances the behavior of the catalyst, leading to significantly improved biodiesel yields.

3.2.2. Effect of temperature and IL concentration during synergy with plasma

Chemical reactions are always affected by increasing temperature, as it positively affects the average speed and rate of movement of the reacting molecules and leads to the formation of

products faster. The effects of changing the temperature and catalyst concentration during synergism with plasma on the esters yield were studied using the fixed conditions of 6:1 molar ratio of methanol to fat and an agitation rate of 600 rpm for 60 min. As can be observed in Figure 4, increasing catalyst loading with increasing temperature had a positive effect on the product yield. However, when temperatures were applied between 40 to 60 °C, increasing the catalyst beyond 5.5 wt% did not cause any significant improvement in yield. It was also noted that the temperatures of 55 °C and 60 °C gave almost identical results. Therefore, 5.5 wt% and 55 °C were chosen as ideal and suitable factors for this reaction.

Increasing the temperature above 60 °C gave reasonable results with catalyst concentrations of 3 wt% and 3.5 wt%, although the yields decreased when compared with those at lower temperatures (40–60 °C). Suddenly, by increasing concentrations to 4–6%, noticeable and significant declines in yields were observed. The reason for this may be that methanol has a boiling point of about 64 °C, and when temperatures applied in this study are 65 and 70 °C, the alcohol reaches the boiling point, and throughout the reaction, there is an almost constant molar percentage of methanol evaporated, suspended, and stable at the top of the reactor—knowing that methanol plays two roles in this reaction, as a basic reactant and as a

solvent for both fats and viscous Oct₃AMHSO₄. The dispersion of methanol as an evaporated fraction and as a solvent led to a reduction in the molar rate (which is supposed to be 6 moles per mole of fat) in the reversible transesterification reaction medium, which may have encouraged the products to return and convert into reactants at the expense of the yield.

Regarding the effect of synergistic catalysis with plasma, it is known that the electrons and ions in the gas that make up the plasma are exposed to a strong electric field, producing hot and energetic ions [21], [22]. Therefore, it was necessary to specifically review the effect of temperature during this reaction and exploit it to obtain the optimal. It is common knowledge that an IL is a type of liquid that is composed of ions. At the same time, plasma is defined as negative electrons and positively charged ions formed due to the separation of atoms in the plasma from their negatively charged electrons [31], [33]. In this reaction, the combination of plasma and IL is thought to have created an abundance of positive and negative charges, giving them a greater ability to rapidly catalyze the reaction at low temperatures and create a high yield. This synergism may have several unique properties that make it adaptable and configured to suit the conditions of any other reaction and to address any obstacles that may arise in catalysis by IL.

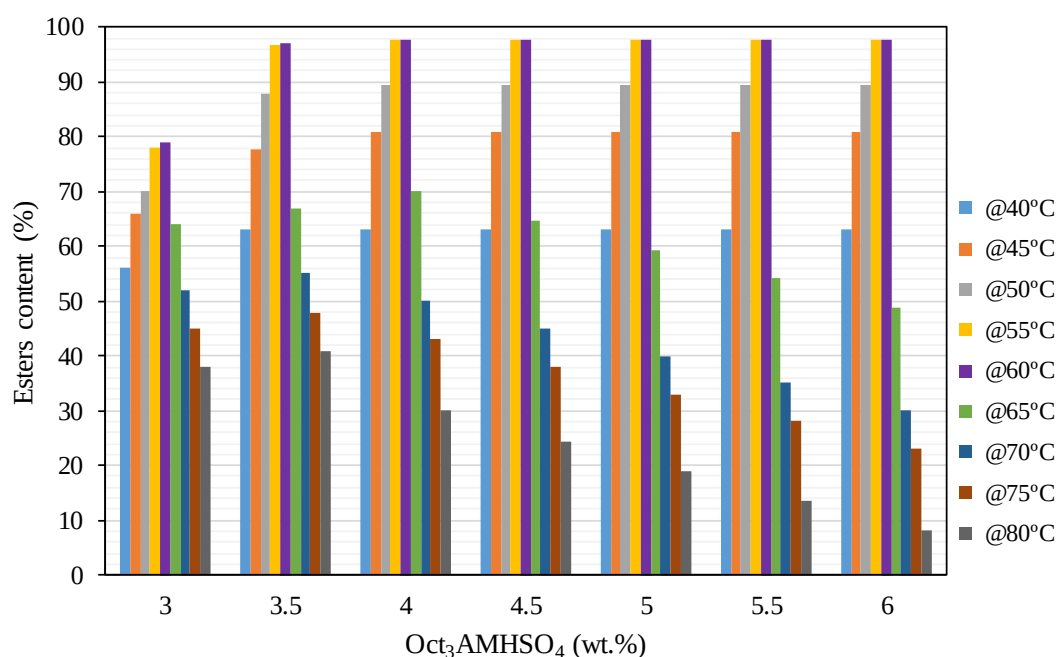


Figure 4. Effect of temperature and IL concentration on esters content

3.2.3. Effect of reaction time during synergy with plasma

The effect of reaction time was studied using the parameters verified above, which were 3.5 wt% Oct₃AMHSO₄ and 55 °C, keeping the molar ratio and stirring rate constant at 6:1 and 600 rpm, respectively. The test covered periods of 15 and 30-120 min. Figure 5 shows that at a reaction time of 15 min, a low percentage of yield (34.2%) was obtained. At a reaction time of 30 to 45 min, a steady improvement was seen as biodiesel, reached 84.3%. Then, it reached a high yield of 97.4% within 60 min and remained unchanged until 75 min of reaction. As shown in the Figure, the yield suddenly deteriorated at a reaction time of 90 to 120 min, reaching about 77.3%. This drop in yield will continue as long as the reaction continues because the transesterification reaction

is reversible, so increasing the reaction time beyond a certain time causes a decrease typically in biodiesel production due to the loss of esters in favor of fat regeneration.

3.2.4. Oct₃AMHSO₄ recyclability and repeatability

Figure 6 shows the performance and recyclability of the catalyst after multiple recovery cycles. As can be expected, after 5 runs there no apparent differences in the yield. These results indicate that, under similar reaction conditions, it can maintain its effectiveness over multiple uses and can be used repeatedly without compromising its efficiency or performance. This is important because repeatability is essential for reducing costs and waste.

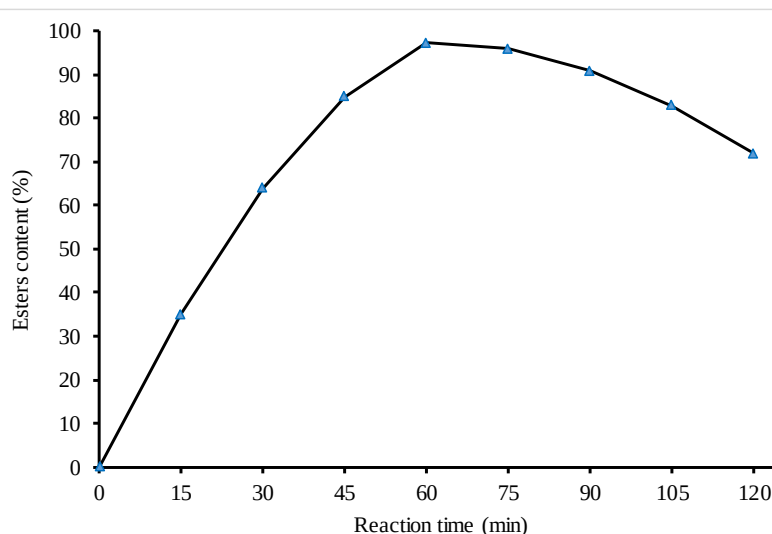


Figure 5. Effect of reaction time on esters content

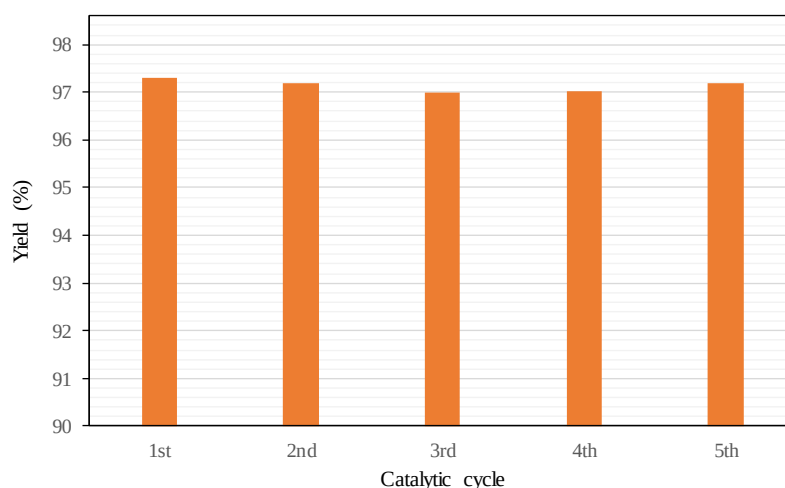


Figure 6. The recyclability of the Oct₃AMHSO₄ with plasma: transesterification conditions conducted, 55 °C, 6:1 molar ratio and 600 rpm for 60 min

4. Conclusion

The importance of this study is that it used troublesome waste, such as low-cost chicken skin, as feedstock for biodiesel production. In addition, compared with previous research, IL was used as a green catalyst under the action of low temperature with acceptable reaction time and a reasonable amount of methanol, which facilitated and reduced the final product separation process costs. In addition, recycling the catalyst has shown promising results with the possibility of reusing it many times, which is also in the interest of reducing production costs. Previous studies have focused on biodiesel production to maintain the catalytic efficiency of ILs at temperatures above 100 °C, but no research has addressed enhancing IL efficiency using plasma at lower temperatures when chicken skin is transesterified. By combining plasma activation with IL catalyst, the transesterification reaction achieved a remarkable biodiesel yield exceeding 97% under moderate conditions (60 °C), with a suitable molar ratio, within a 60-min reaction timeframe, highlighting the potential of this synergistic approach for efficient biodiesel production. However, until now, the nature of the interaction of the plasma's active state on the surfaces of the catalyst has not been understood, nor has the manner and nature of the movement of its electrons. This shortage limits the application and predictability of the effect of plasma catalysis or even activation when dealing with certain reactions that suffer from a lack of product or reaction rate. The IL in this research does not pose any environmental challenges due to its ease of recycling as no catalyst was lost during any of the recycling processes.

Following advancements in this new technology, which utilize affordable feedstocks, resolve catalyst issues, and enhance the current process, we expect the industrial technology to focus on improving production efficiency in dedicated plants to meet the rising demand for green diesel and environmental challenges.

Acknowledgements

The author would like to thank the University of Nizwa – Sultanate of Oman for providing lab equipment and research funding as well as the University of Nizwa Writing Center for all the

valuable comments while proofreading this manuscript.

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

Funding

This research is funded by the University of Nizwa – Sultanate of Oman

Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

References

- [1] Fereidoun *et al.*, "Mean Percentage of Skin and Visible Fat in 10 Chicken Carcass Weight," *International Journal of Poultry Science*, vol. 6, no. 1, pp. 43–47, Dec. 2006, doi: 10.3923/ijps.2007.43.47.
- [2] C. Aquino, "Brazil: Poultry and Products Annual," 2024. [Online]. Available: <https://www.fas.usda.gov/data/brazil-poultry-and-products-annual-10>
- [3] V. Feddern *et al.*, "Physico-chemical composition, fractionated glycerides and fatty acid profile of chicken skin fat," *European Journal of Lipid Science and Technology*, vol. 112, no. 11, pp. 1277–1284, Nov. 2010, doi: 10.1002/ejlt.201000072.
- [4] ReportLinker, "Oman Poultry Meat Industry Outlook 2022 - 2026," ReportLinker. [Online]. Available: <https://www.reportlinker.com/clp/country/1828/726424>
- [5] F. Perera, "Pollution from Fossil-Fuel Combustion is the Leading Environmental Threat to Global Pediatric Health and Equity: Solutions Exist," *International Journal of Environmental Research and Public Health*, vol. 15, no. 1, p. 16, Dec. 2017, doi: 10.3390/ijerph15010016.
- [6] K. Winangun, Y. Winardi, I. Puspitasari, N. S. Akhmad, R. D. Ardika, and S. Ozer,

- "Reducing Exhaust Emissions from Palm Oil Biodiesel Diesel Engines by Adding Hydrogen Gas," *Automotive Experiences*, vol. 7, no. 3, pp. 502–512, Dec. 2024, doi: 10.31603/ae.12404.
- [7] J. Milano *et al.*, "A Comprehensive exploration of jatropha curcas biodiesel production as a viable alternative feedstock in the fuel industry – Performance evaluation and feasibility analysis," *Mechanical Engineering for Society and Industry*, vol. 4, no. 1, pp. 17–37, Apr. 2024, doi: 10.31603/mesi.10610.
- [8] P. Yadav, M. Jagtap, P. Karande, and P. M., "Characterization of animal fat-based biodiesel fuel in the Indian context for optimized sustainable production and management," *Sustainable Chemistry for Climate Action*, vol. 6, p. 100082, Jun. 2025, doi: 10.1016/j.scca.2025.100082.
- [9] A. Kolakoti, M. Setiyo, and B. Waluyo, "Biodiesel Production from Waste Cooking Oil: Characterization, Modeling and Optimization," *Mechanical Engineering for Society and Industry*, vol. 1, no. 1, pp. 22–30, Jul. 2021, doi: 10.31603/mesi.5320.
- [10] A. I. EL-Seesy, M. E. Elshobary, and Z. He, "Biofuel versus fossil fuel," in *Handbook of Algal Biofuels*, Elsevier, 2022, pp. 181–193. doi: 10.1016/B978-0-12-823764-9.00027-3.
- [11] K. Malik *et al.*, "Biofuels Production: A Review on Sustainable Alternatives to Traditional Fuels and Energy Sources," *Fuels*, vol. 5, no. 2, pp. 157–175, May 2024, doi: 10.3390/fuels5020010.
- [12] N. Mohanrajhu and S. Sekar, "Hydrogen-Enriched Combustion of Chicken Skin Waste Biodiesel in Diesel Engines: Performance and Emission Characteristics," *Chemistry Africa*, vol. 8, no. 6, pp. 2395–2407, Aug. 2025, doi: 10.1007/s42250-025-01356-3.
- [13] H. Chowdhury *et al.*, "Synthesis of biodiesel from chicken skin waste: an economic and environmental biofuel feedstock in Bangladesh," *Environmental Science and Pollution Research*, vol. 28, no. 28, pp. 37679–37688, Jul. 2021, doi: 10.1007/s11356-021-13424-5.
- [14] Y. A. Elsheikh *et al.*, "In situ Transesterification/Reactive Extraction of Castor Bean Seeds Assisted by Flying Jet Plasma for Biodiesel Production," *Applied Chemical Engineering*, vol. 33, no. 5, pp. 538–544, 2022, doi: 10.14478/ace.2022.1086.
- [15] H. M. Khan *et al.*, "Current scenario and potential of biodiesel production from waste cooking oil in Pakistan: An overview," *Chinese Journal of Chemical Engineering*, vol. 27, no. 10, pp. 2238–2250, Oct. 2019, doi: 10.1016/j.cjche.2018.12.010.
- [16] G. Raghavendr and R. Jambulinga, "Comprehensive Study on Biodiesel Produced from Waste Animal Fats-A Review," *Journal of Environmental Science and Technology*, vol. 11, no. 3, pp. 157–166, Apr. 2018, doi: 10.3923/jest.2018.157.166.
- [17] P. Maheshwari *et al.*, "A review on latest trends in cleaner biodiesel production: Role of feedstock, production methods, and catalysts," *Journal of Cleaner Production*, vol. 355, p. 131588, Jun. 2022, doi: 10.1016/j.jclepro.2022.131588.
- [18] R. L. Vekariya, "A review of ionic liquids: Applications towards catalytic organic transformations," *Journal of Molecular Liquids*, vol. 227, pp. 44–60, Feb. 2017, doi: 10.1016/j.molliq.2016.11.123.
- [19] Q. Wu, H. Chen, M. Han, D. Wang, and J. Wang, "Transesterification of Cottonseed Oil Catalyzed by Brønsted Acidic Ionic Liquids," *Industrial & Engineering Chemistry Research*, vol. 46, no. 24, pp. 7955–7960, Nov. 2007, doi: 10.1021/ie070678o.
- [20] M. M. Fan, J. J. Zhou, Q. J. Han, and P. B. Zhang, "Effect of various functional groups on biodiesel synthesis from soybean oils by acidic ionic liquids," *Chinese Chemical Letters*, vol. 23, no. 10, pp. 1107–1110, Oct. 2012, doi: 10.1016/j.cclet.2012.07.009.
- [21] P. Mierczynski, A. Mierczynska-Vasilev, M. Szyrkowska-Jozwik, and K. Vasilev, "Atmospheric plasma in the preparation and pre-treatment of catalytic materials – A mini review," *Catalysis Communications*, vol. 187, p. 106839, Feb. 2024, doi: 10.1016/j.catcom.2023.106839.
- [22] J. H. Davis, C. M. Gordon, C. Hilgers, and P. Wasserscheid, "Synthesis and Purification of Ionic Liquids," in *Ionic Liquids in Synthesis*, Wiley, 2002, pp. 7–40. doi:

- 10.1002/3527600701.ch2.
- [23] K. B. Kiradjeiev, V. Nikolakis, I. M. Griffiths, U. Beuscher, V. Venkateshwaran, and C. J. W. Breward, "A Simple Model for the Hygroscopy of Sulfuric Acid," *Industrial & Engineering Chemistry Research*, vol. 59, no. 10, pp. 4802–4808, Mar. 2020, doi: 10.1021/acs.iecr.9b06018.
- [24] Y. S. Khoo, T. C. Tjong, J. W. Chew, and X. Hu, "Techniques for recovery and recycling of ionic liquids: A review," *Science of The Total Environment*, vol. 922, p. 171238, Apr. 2024, doi: 10.1016/j.scitotenv.2024.171238.
- [25] W. Mengjin, J. Lixia, L. Suling, Q. Zhigang, W. Sainan, and Y. Ruosi, "Interfacial performance of high-performance fiber-reinforced composites improved by cold plasma treatment: A review," *Surfaces and Interfaces*, vol. 24, p. 101077, Jun. 2021, doi: 10.1016/j.surfin.2021.101077.
- [26] J. Mravlje, M. Regvar, and K. Vogel-Mikuš, "Development of Cold Plasma Technologies for Surface Decontamination of Seed Fungal Pathogens: Present Status and Perspectives," *Journal of Fungi*, vol. 7, no. 8, p. 650, Aug. 2021, doi: 10.3390/jof7080650.
- [27] M. M. Gui, K. T. Lee, and S. Bhatia, "Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock," *Energy*, vol. 33, no. 11, pp. 1646–1653, Nov. 2008, doi: 10.1016/j.energy.2008.06.002.
- [28] G. Knothe, "Dependence of biodiesel fuel properties on the structure of fatty acid alkyl esters," *Fuel processing technology*, vol. 86, no. 10, pp. 1059–1070, 2005, doi: 10.1016/j.fuproc.2004.11.002.
- [29] S. K. Hoekman, A. Broch, C. Robbins, E. Cenicerros, and M. Natarajan, "Review of biodiesel composition, properties, and specifications," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 1, pp. 143–169, Jan. 2012, doi: 10.1016/j.rser.2011.07.143.
- [30] A. E. Atabani *et al.*, "Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production," *Renewable and Sustainable Energy Reviews*, vol. 18, pp. 211–245, Feb. 2013, doi: 10.1016/j.rser.2012.10.013.
- [31] A. Bogaerts, "Editorial Catalysts: Special Issue on Plasma Catalysis," *Catalysts*, vol. 9, no. 2, p. 196, Feb. 2019, doi: 10.3390/catal9020196.
- [32] V. Kroeze, L. Braakhuis, A. J. B. ten Kate, and S. R. A. Kersten, "Determination of the Minimum Catalyst Amount in the Design of Catalytic Distillation Columns," *Industrial & Engineering Chemistry Research*, vol. 60, no. 28, pp. 10254–10264, Jul. 2021, doi: 10.1021/acs.iecr.1c01024.
- [33] Z. Wang *et al.*, "Catalyst Preparation with Plasmas: How Does It Work?," *ACS Catalysis*, vol. 8, no. 3, pp. 2093–2110, Mar. 2018, doi: 10.1021/acscatal.7b03723.